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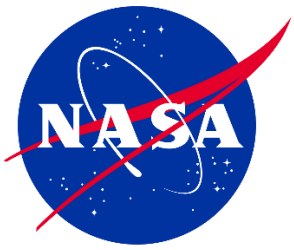

Hydrofluoroether (HFE) Cleaning Fluid Replacement and Qualification

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September 2026

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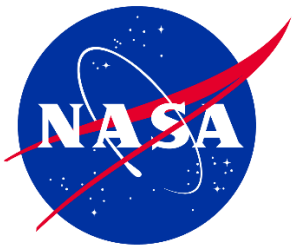

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National Aeronautics and
Space Administration

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September 2026

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NASA Engineering and Safety Center
Technical Assessment Report

Hydrofluoroether (HFE) Cleaning Fluid Replacement and Qualification

TI-23-01850

Andrew Chaloupka, NESC Lead

Janelle Coutts, Technical Lead

May 14, 2026

Report Approval and Revision History

NOTE: This document was approved at the May 14, 2026, NRB.

Approved: Michael Kirsch Digitally signed by Michael Kirsch Date: 2026.06.08 11:14:11 -05'00'

NESC Director

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	NESC Chief Engineer's Office	May 14, 2026

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Technical Assessment Report

1.0 Notification and Authorization

Requesting Person: Joe Pellicciotti, NASA Chief Engineer

Affected Organizations/Key Stakeholders:

- Programs: Commercial Crew Program (CCP), Space Launch System (SLS), Human Landing System (HLS), Multipurpose Crew Vehicle (MPCV), Exploration Ground Systems (EGS), International Space Station (ISS), Launch Services Program (LSP), Gateway, and NASA Engineering
- Center Precision Cleaning Facilities: Kennedy Space Center Component Cleaning and Chemical Analysis Facility (KSC-CRCA), White Sands Test Facility (WSTF), Marshall Space Flight Center (MSFC), Stennis Space Center (SSC), Michoud Assembly Facility (MAF), Johnson Space Center (JSC), Neutral Buoyancy Laboratory (NBL), Glenn Research Center (GRC), Wallops Island
- Agencies/Commercial Entities with NASA Partnerships: Department of War (Space Force, Air Force, Defense Logistics Agency, National Reconnaissance Office), Boeing, SpaceX
- European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), Thales Alenia Space Italia (TASI), Canadian Space Agency (CSA), Deutsches Zentrum für Luft- und Raumfahrt (DLR), Centre National D'études Spatiales (CNES)

NESC Lead: Andrew Chaloupka, Associate Principal Engineer, MSFC

Technical Lead: Janelle Coutts, Branch Technical Lead, KSC

Description of Request: 3M, the manufacturer of several hydrofluoroethers (HFEs) used by the Agency, Department of Defense (DoD), and commercial entities partnered with both agencies, has announced intentions to end production of their entire per/polyfluoroalkyl substances (PFAS), which include HFEs, by the end of 2025. Throughout the Agency, HFEs (specifically, HFE-7100) are used in precision cleaning processes for ground and flight hardware to remove fluorinated grease and hydrocarbon contamination with no qualified and approved alternative identified. An assessment to identify, test, and qualify replacement solvent(s), aqueous detergent(s), or alternative 'solventless' technology is needed to meet Agency demands for precision cleaning, especially for use in oxygen-servicing hardware. HFEs (specifically, HFE-7200) are also used as a heat transfer fluid in immersive cooling applications where power density is higher than what typical air cooling can remove. Currently, HFE-7200 is used in the thermal control systems for both Orion and Gateway, with no qualified and approved alternatives. To address the heat transfer application, a replacement fluid will be studied for thermal requirement parameters and materials compatibility.

Request Submitted	February 16, 2023
Initial Evaluation Approved	February 16, 2023
Assessment Plan Approved	April 6, 2023
Team Kickoff Meeting	March 4, 2024
Stakeholder Briefing (Interim Status Report)	June 7, 2024
Final Report Delivery and Stakeholder Update	May 14, 2026

2.0 Signatures

Submitted by: NESC Lead

ANDREW CHALOUPKA

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Mr. Andrew Chaloupka

Significant Contributors

Janelle Coutts

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Dr. Janelle L. Coutts

Lorlyn Reidy

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Dr. Lorlyn P. Reidy

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team Members

Name	Discipline	Organization (include host Center)
Core Team		
Andrew Chaloupka	NESC Lead	MSFC/C103
Janelle Coutts	Technical Lead	KSC/NE-L3
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William Battle	Precision Cleaning	MSFC/EM22
Jesus Dominguez	Particle Cleaning Modeling	MSFC/ES62
Joseph Fillion	Alternative Cleaning Technologies	MSFC/EM22-ESSCA
Efram Goldberg	Precision Cleaning/Materials Compatibility	KSC/LASSOII-2100
Joy Hamilton	Materials Compatibility	WSTF/RF111
Susana Harper	Oxygen Compatibility	WSTF/RF111
Christopher Henry	Alternative Cleaning Technologies	MSFC/EM22
Donald Kahn	Precision Cleaning	KSC/LASSOII-3000
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Jonathan Mott	Materials Compatibility	KSC/NE-L7
Stephen Peralta	Oxygen Compatibility	WSTF/RF111
Lorlyn Reidy	Alternative Cleaning Technologies	MSFC/EM22
David Rinderknecht	Precision Cleaning/Materials Compatibility	KSC/NE-L3
Paul Schrader	Precision Cleaning	MSFC/EM22
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Virginia (Jennie) Ward	Oxygen Compatibility	WSTF/RF111
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Katherine McGinnis	Precision Cleaning/Payloads (Retired)	GRC/LMA0
Tien Nguyen	Precision Cleaning	JSC/ES311
Don Parker	NESC Principal Engineer	NESC/KSC/C103
Mike Pedley	Precision Cleaning/Materials Compatibility	JSC/ES411
Harold Rick Ross	Precision Cleaning	SSC/WYE
Darrel Shoup	Precision Cleaning	WSTF/RH111
John Steele	Precision Cleaning/Environmental Control, Life Support, Crew Systems, and Spacesuits Technical Discipline Team	MRI Technologies
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Name	Discipline	Organization (include host Center)
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Christa Hahn	Technical Editor	AMA/LaRC

3.1 Acknowledgements

The NESC team would like to thank the KSC and MSFC Engineering Directorates for providing timely testing and data delivery in support of the NESC Assessment. This effort required substantial research and development, close coordination with ASTM and multiple vendors, and innovative problem-solving to address challenges encountered as we pushed the limits of existing equipment and standards.

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4.0 Executive Summary

Mr. Joe Pellicciotti, NASA Chief Engineer, requested the NASA Engineering and Safety Center (NESC) provide an independent assessment of Agency readiness for the discontinuation of 3M Novec™ HFE-7100 and related hydrofluoroether (HFE) products, which are widely used for precision cleaning and thermal control applications across NASA programs and facilities. On December 20, 2022, 3M announced its intent to cease all manufacturing of per- and polyfluoroalkyl substance (PFAS), including HFEs, by the end of 2025. This action, combined with increasing regulatory restrictions on PFAS in the United States and internationally, presents a significant risk to Agency operations that depend on these materials.

Throughout the Agency, Novec HFE-7100 is used in precision cleaning processes for ground and flight hardware to remove fluorinated grease and hydrocarbon contamination, with no qualified and approved alternative identified. It is also the sole approved solvent for final flushing and cleanliness verification of oxygen system component cleaning at multiple NASA precision cleaning facilities. In addition, Novec HFE-7100 and HFE-7200 are used as surrogate fluids for hazardous propellants and as heat transfer fluids in immersive cooling applications for high-power-density systems. The assessment was initiated to identify, test, and qualify replacement solvent(s), aqueous detergent(s), and alternative 'solventless' technologies to meet Agency demands for precision cleaning, especially for use in oxygen-servicing hardware, as well as identify, test, and qualify replacement thermal fluids.

The NESC assessment was structured in three primary tasks: (1) identification, testing, and qualification of replacement solvents for Novec HFE-7100; (2) evaluation of alternative precision cleaning technologies; and (3) initial assessment of replacement fluids for thermal control systems using Novec™ HFE-7200. This report addresses Tasks 1 and 2, with Task 3 to be addressed in a future deliverable.

The assessment team included representatives from NASA programs — Commercial Crew Program (CCP), Space Launch System (SLS), Human Landing System (HLS), Multipurpose Crew Vehicle (MPCV), Exploration Ground Systems (EGS), International Space Station (ISS), Launch Services Program (LSP), Gateway, and NASA Engineering — Agency precision cleaning facilities, and commercial/government partners. The team's approach included: (1) surveying Agency and partner facilities for current Novec HFE-7100 usage and readiness for transition; (2) laboratory-scale screening of commercially available replacement solvents for cleaning efficacy and materials compatibility; (3) evaluation of autoignition temperature (AIT) and mechanical impact thresholds for oxygen system compatibility; and (4) proof-of-concept testing of alternative cleaning technologies, including aqueous detergents/systems, supercritical CO_2, cryogenic aerosol, plasma, UV-ozone, magnetically optimized fluids (MOF), and induced charge active filtration (ICAF).

The assessment found that Solstice performance fluid (PF)/PF-(high purity) HP (trans-1-chloro-3,3,3-trifluoroprop-1-ene) is a viable Novec HFE-7100 replacement for small-to-medium throughput facilities with compatible equipment and can be recycled on site. However, its physical properties (e.g., lower boiling point, higher vapor pressure) make transitioning to Solstice PF/PF-HP challenging for large, high-throughput operations without significant capital investment. Among 'drop-in' solvent candidates, Amolea AS-300 and Opteon SF33 performed best in laboratory mixed contaminant removal challenges, with BestSolv® Sierra as a strong alternative. Metals and soft goods compatibility testing revealed that 4340 low-alloy steel is

particularly susceptible to several candidates, and review of the data for other metals and softgoods should be completed to ensure compatibility prior to use. For oxygen system cleaning, Opteon SF33 and BestSolv Sierra demonstrated AIT values above 204 °C, making them preferred for critical applications over Amolea AS-300. However, Amolea AS-300 may be acceptable for use in breathing air/compressed air systems and additional steps may be employed to allow for use in enriched oxygen systems. Selection of a replacement solvent must be a balance in the results from the cleaning efficiency studies, material/system compatibility results (e.g., metals, soft goods, oxygen systems, etc.), and occupational safety considerations.

Aqueous and supercritical CO_2 cleaning are effective for specific applications but require substantial facility investment. Dry cleaning methods (e.g., cryogenic aerosol, plasma, UV-ozone) are promising but not yet mature for broad NASA adoption. Magnetically optimized fluid (MOF) and induced charge active filtration (ICAF) prototypes did not show significant performance improvements under test conditions but may offer long-term sustainability benefits with further development.

In summary, the NESC identified 20 Findings, 15 Observations, and 12 Recommendations that center on: (1) determining the most suitable replacement(s) for Novec HFE-7100 in Agency cleaning operations; (2) fully quantifying the cleaning efficacy, materials compatibility, and oxygen system safety of candidate solvents; (3) assessing the readiness and facility impacts of alternative cleaning technologies; and (4) updating NASA standards and specifications to allow for molecularly equivalent products and new drop-in options with clear purity and compatibility requirements. The NESC recommends continued monitoring of regulatory developments, ongoing pilot testing of alternative technologies, and proactive updates to Agency standards to ensure mission continuity and compliance.

5.0 Assessment Plan

The assessment was broken into three distinct tasks, Tasks specific to replacement of HFE-7100 are detailed below:

5.1 Task 1: Identification, Testing, and Qualification of Replacement Solvents for Novec HFE-7100

5.1.1 Task 1A: Feasibility of Implementing Solstice Performance Fluid (PF) Usage Access at Agency/External Entities for Precision Cleaning

Solstice PF was previously examined in the laboratory [1] and adopted for use at several NASA locations including Stennis Space Center (SSC) and Michoud Assembly Facility (MAF). Due to its drastically different physical properties from HFE-7100, there was a need to understand what cleaning processes these facilities utilized, their processing space(s) and cleaning throughput, and how Solstice was implemented for use to determine if adoption at other Agency precision cleaning facilities was feasible. For this subtask, a survey of various Agency cleaning facilities was completed, and an in-person technical exchange with experts at SSC and MAF was held to understand their Solstice transition. Adoption considerations were gathered for dissemination to the broader precision cleaning community.

5.1.2 Task 1B: Evaluation of 'Drop In' Replacement Candidates for Novec HFE-7100

To meet near-to-mid-term requirements and provide a stop-gap solution for Agency precision cleaning, a survey of candidates marketed as suitable replacements was completed and top candidates were evaluated at the laboratory scale. Testing included the following:

- Baseline non-volatile residue (NVR) of the replacement candidate
- Hydrocarbon miscibility
- Individual target contaminant removal challenge; results provided down selection of candidates for additional testing
- Combined contaminant removal challenge on complex fittings and coupons
- Metal and nonmetal compatibility
- AIT determination

5.2 Task 2: Identification and Initial Testing of Alternative Precision Cleaning Technologies

Task 1B served to provide near-to-midterm solutions for Agency precision cleaning but is not likely to provide a long-term, sustainable solution with anticipated regulatory restrictions for PFAS materials. Task 2 of the assessment focused on identifying new and evolving technologies for precision cleaning that, if successful, would allow for minimization or elimination of PFAS-type solvent use. Objectives included a survey of technologies and state-of-the-art for each, investigation of feasibility through laboratory-scale testing if not already completed, and documentation of considerations for further technology maturation and/or investment.

6.0 Problem Description and Background

6.1 HFEs, 3M Notification, and Increased Restrictions on Perfluorinated Chemicals

HFE organic solvents were developed as a replacement to ozone depleting solvents such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and perfluorocarbons (PFCs). On December 20, 2022, 3M, the manufacturer of several HFEs used throughout the Agency, released a notice to their customers outlining the company's plan to exit per- and polyfluoroalkyl substance manufacturing and use of PFAS in their product portfolio by the end of 2025 (Figure 1) [2].

3M Electronics Materials Solutions Division

3M Center, Building 223-3S-32
St. Paul, MN, USA 55144-1000

3M

December 20, 2022

Dear Valued Customer,

3M today announced it plans to exit per- and polyfluoroalkyl substance (PFAS) manufacturing and work to discontinue use of PFAS in its product portfolio by the end of 2025. This portfolio decision is based on careful consideration and a thorough evaluation of the external landscape, including multiple factors such as accelerating regulatory trends focused on reducing or eliminating the presence of PFAS in the environment and changing stakeholder expectations.

This impacts products/product families you purchase from 3M listed in Appendix 1. Unfortunately, supply of most of these products continues to be impacted by global supply challenges and strong industry demand exceeding current capacity. Some of the products are also impacted by ongoing force majeure events. We will continue to take all reasonable steps to avoid supply disruptions, but we anticipate that our ability to supply will continue to be constrained.

3M will continue to fulfill contractual obligations during the transition period. Please note that regardless of any order acknowledgement, 3M may not be able to supply your orders due to continuing force majeure events and supply constraints, and we strongly urge customers to find alternative sources of supply.

3M will manage customer last time buy requests based on availability of supply, and we will work with customers to determine specific needs and put in place an action plan to help ensure an orderly transition. 3M does not currently anticipate stockpiling these products.

We understand you may have questions concerning this announcement. Please contact your 3M sales representative, who will work with you to the best of their ability to help support.

Sincerely,

David N. Schneider

David N. Schneider
Vice President, Chemicals and Semiconductor
3M Company, Electronics Materials Solutions Division

Figure 1. 3M Notification Letter to Customer Base [2].

Included in the listing of around 15,000 products to be discontinued was Novec 7100 (HFE-7100) engineering fluid, a solvent used across the Agency for precision cleaning of ground and flight hardware to remove fluorinated grease, hydrocarbon contamination, and particulate contamination. HFE-7100 is of particular importance for multiple NASA precision cleaning facilities as it is frequently the sole approved solvent for the final flushing and cleanliness verification of oxygen system component cleaning. In addition, HFE-7100 is often a safe-to-handle surrogate for nitrogen tetroxide for system testing by the spaceflight propulsion community.

The increasing desire to reduce or eliminate PFAS presence in the environment is intermingled with, and one of the drivers for, 3M's decision to exit the PFAS production business. In the United States, two major, current, regulatory drivers include the Toxic Substance Control Act (TSCA) of 1976/Frank R. Lautenberg Chemical Safety for the 21st Century Act; and the American Innovation and Manufacturing (AIM) Act of 2020. In addition, the number of reports on the PFAS contamination in water supplies and possible associated health risks were increasing.

TSCA provides the Environmental Protection Agency (EPA) with authority to require reporting, record-keeping and testing requirements, and restrictions relating to chemical substances and mixtures [3], with the goal of enhancing public safety. Annual plans for risk evaluations are published by the EPA; in 2019, 20 substances received a designation of a High-Priority Chemical Substance for Risk Evaluation with timelines for final risk evaluations to be completed between the end of calendar year 2024, and end of calendar year 2026 [4]. Included in this current list is *trans*-1,2-dichloroethylene (risk evaluation estimated no later than December 2026), commonly used in cleaning solvent formulations, among other chlorinated substances. Final evaluations can lead to altered exposure requirements, reduced production and use allowances, and the need to find alternative substances for critical processes.

The AIM Act authorizes the EPA to address hydrofluorocarbons (HFCs) with authority in three main areas: phase down of production and consumption of listed HFCs, management of listed HFCs and their substitutes, and facilitation of the transition to next-generation technologies through sector-based restrictions [5]. A total of 18 HFCs, and any isomers of them, are called out as a regulated substance in the AIM Act [6]; one of the 18 is decafluoropentane, the compound used in Vertrel XF (and HFC portion of Vertrel MCA) cleaning solvent. While these regulations can face significant changes with changing political climates, they have significantly impacted the current state of the perfluorinated market for applications affecting NASA and beyond.

In addition to increased regulation and risk assessment in the United States, foreign entities have similar regulatory initiatives and laws in place also restricting PFAS-type materials. The regulation of the Registration, Evaluation, Authorization, and restriction of Chemicals (REACH) is the main European Union (EU) law designed to protect human health and the environment from risks posed by chemicals [7]. Similar to TSCA, REACH aims to ensure protection of human health and the environment against harmful substances, and includes a restriction process for certain substances of very high concern if they pose unacceptable risk to health or the environment. The European Chemicals Agency, ECHA, aims to complete an evaluation of an EU-wide restriction on per- and polyfluorinated substances by the end of 2026; results of the evaluation could affect not only Agency missions with NASA's European partners that currently utilize these chemicals, but also broader US industries as European manufacturers of PFAS and PFAS-containing commodities are restricted.

An assessment to identify, test, and qualify replacement solvent(s), aqueous detergent(s), or alternative “solventless” technology wasneeded to meet Agency demands for precision cleaning, especially for use in oxygen-servicing hardware. Evaluation included addressing cleaning efficiency, flammability requirements, and materials compatibility. The long-term goal is to reduce dependability on solvents facing a risk of regulation due to their environmental impacts.

6.2 Novec HFE-7100

Novec 7100 (HFE-7100) consists of two inseparable isomers of methoxy-nonafluorobutane (CAS Numbers 163702-08-7 and 163702-07-6) with essentially identical properties. The fluid is clear and colorless, with zero ozone depletion potential, high thermal stability, non-flammability, and low toxicity. It is advertised as ideal for use in vapor-degreasing applications as a pure, azeotropic component, or co-solvent parts cleaner [8]. Its properties are outlined in Table 1.

Table 1. Novec HFE-7100 Properties

Property	Value
Formula	$C_4F_9OCH_3$ (isomers of $(CF_3)_2CFCF_2OCH_3$ and $CF_3CF_2CF_2CF_2OCH_3$)
Molecular Weight (g/mol)	250
Boiling Point (°C)	61
Freezing Point (°C)	-135
Liquid Density (g/mL)	1.52
Surface Tension (dynes/cm)	13.6
Solubility of Solvent in Water (ppm)	12
Solubility of Water in Solvent (ppm)	95
Vapor Pressure @ 25 °C (mmHg)	202
Ozone Depletion Potential (ODP)	0.00
Global Warming Potential (GWP)	320
Atmospheric Lifetime (years)	4.1
Flashpoint (°C)	None
Flammability Range in Air	None
Exposure Guidelines (8-hour time-weighted average, ppm)	750

HFE-7100, along with Vertrel MCA, Vertrel XF, and HCFC 225, was largely adopted for use by NASA facilities in the late-1990s/early-2000s with the elimination of CFC 113 as part of the Montreal Protocol and Clean Air Act. It has remained in use at a majority of Agency precision cleaning facilities as the final flush and verification solvent for both ground support equipment and flight components, especially for oxygen and oxidizer systems. Of the solvents included in most Center and/or Program requirements/specifications, HFE-7100 remains the primary cleaning solvent for oxygen and oxidizer systems with no other current (non-retired/eliminated) alternatives.

7.0 Testing Results and Analysis

7.1 Task 1A: Feasibility of Implementing Solstice Performance Fluid (PF) Usage Access Agency/External Entities for Precision Cleaning

7.1.1 2015 Replacement of AK225 Report

In 2015, a report [1] was released by a joint effort between MSFC, SSC, and WSTF for replacement of Hydrochlorofluorocarbon-225 (HCFC-225) in a response to the EPA's stratospheric ozone regulations in 40 CFR 82.15, prohibiting sale of virgin HCFCs for solvent uses on January 1, 2015 [9]. The resulting replacement solvent designated for implementation at MSFC and SSC was Honeywell's Solstice PF. Extensive laboratory testing on cleaning efficacy and materials compatibility was highlighted in the report; no additional laboratory testing was completed as part of the current effort as it was considered to be duplicative of these efforts.

7.1.2 Cleaning Institutions Utilizing Solstice PF Across the Agency

With the significantly different physical properties of Solstice PF, particularly the boiling point and vapor pressure, there was a need to better understand how its use was implemented at SSC and MAF to determine if adoption is feasible at other critical NASA precision cleaning facilities. In June 2023, representatives from the NESC, KSC Engineering Directorate, and KSC-CRCA Facility visited SSC and MAF to better understand the implementation at both facilities. This report documents the different configurations in use at those facilities and suggestions on implementation for others looking for alternatives to HFE-7100.

Solstice PF comprises the compound trans-1-chloro-3,3,3-trifluoroprop-1-ene; there are two main versions for use in precision cleaning with the purity level being the difference (99% w/w minimum purity and 10 ppm w/w maximum NVR for typical grade Solstice PF [10]; 99.5% w/w minimum purity and 2 ppm w/w maximum NVR in the high purity grade [11]). The properties of Solstice PF and HFE-7100 are compared in Table 2.

Table 2. Solstice PF and HFE-7100 Physical, Environmental, and Toxicological Properties [10], [11], [12], [13].

	Solstice PF/PF-HP	**3M Novec HFE-7100**
Chemical Name	*trans*-1-chloro-3,3,3-trifluoroprop-1-ene	Methoxy-nonafluorobutane
Molecular Formula	CF_3-CH=CClH	Consists of two inseparable isomers: $(CF_3)_2CFCF_2OCH_3$ and $CF_3CF_2CF_2CF_2OCH_3$
CAS Number	102687-65-0	163702-08-7 and 163702-07-6
Molecular Weight (g/mol)	130	250
Boiling Point (°C)	19	61
Latent Heat of Vaporization at Boiling Point (kJ/kg)	194	112
Freezing Point (°C)	-107	-135
Vapor Pressure at 25 °C (kPa)	126	26.9
Liquid Density at 25 °C (g/mL)	1.26	1.52
Surface Tension at 25 °C (dyne/cm)	12.7	13.6
Liquid Viscosity at 25 °C (cP)	0.446	0.61
Solubility of Solvent in Water (ppm)	1900 (at 20 °C)	12 (at 25 °C)

	Solstice PF/PF-HP	3M Novec HFE-7100
Solubility of Water in Solvent at 25 °C (ppm)	460	95
Kb Value	25	10
Wetting Index	221	183
NVR (ppm)	<10 or <2, depending on grade	≤2.0
Lower Flammability Limit (vol%)	None	None
Occupational Exposure Limit, OEL, 8-hr Time Weighted Average (ppm)	800	750
Ozone Depletion Potential, ODP	Negligible	0.00
Global Warming Potential, GWP (100-year)	1	320

7.1.2.1 Stennis Space Center Visit, June 2023

In late June 2023, representatives from Kennedy Space Center met with the SSC Lead of the Gas and Materials Science Laboratory, SSC NASA Contracting Officer Representative for the lab, and SSC Engineering Technician to better understand the adoption and implementation of Solstice PF at the facility.

Solstice Use

SSC utilizes 1,000-pound cylinders of the HP-grade Solstice that are stored in an external room and plumbed into the laboratory/shop workspace for ease in handling (Figure 2). NVR is verified on new cylinders to meet specification requirements; it was also noted by the technician that the NVR remains stable even when the cylinder volume is low. One of the decision points for choosing the 1,000-lb cylinder was that an external head pressure can be kept on the tanks to allow for optimized flow for cleaning (60 psi head pressure using gaseous nitrogen was found to be adequate for SSC's cleaning need). Solstice usage was approximated to 3 - 4 cylinders on an annual basis. Additionally, the SSC Gas and Material Science Laboratory (analytical lab) now uses Solstice PF to clean and prepare wipes and swabs for collecting contamination samples from the test complex area; and to clean glassware/ancillary items used for NVR analysis and condensable hydrocarbons. The laboratory's Solstice usage is estimated at one 1,000-lb cylinder over 18 months. Recently, the SSC Field Cleaning Group also changed to Solstice PF for cleaning small items (e.g., fittings, small tube assemblies) that support the test complex areas for propulsion testing; usage volume is unknown for that group.

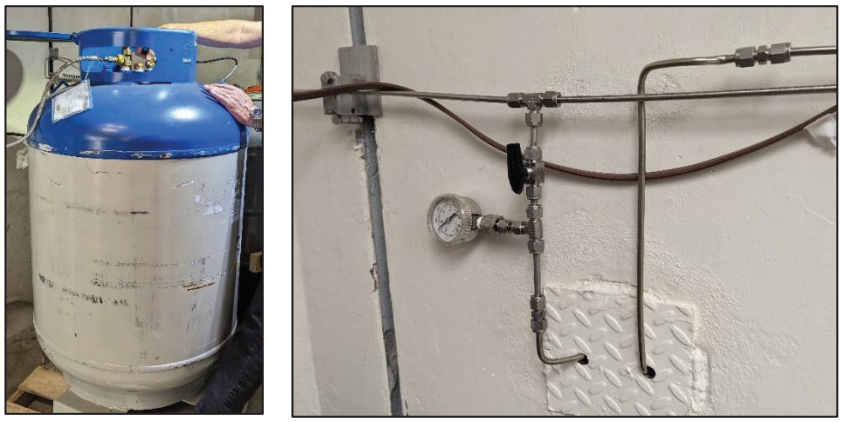


Figure 2. Solstice PF 1,000-lb cylinder (left) and in-lab plumbing for fluid use (right)

Cleaning Volume and Laboratory/Shop Setup

The laboratory/shop area used for processing with Solstice PF contains two laminar flow benches equipped with sample cleaning, NVR processing, and particulate monitoring instrumentation (Figure 3). Isopropyl alcohol (IPA) is often used in a preclean process for the parts with Solstice PF-HP as the validation solvent. There is no recovery of the Solstice at the SSC facility; it is a one-way flow with capture of any excess fluid in a waste container. Waste volumes are minimal due to low processing levels and evaporation of the solvent. The technicians who routinely process parts with Solstice suggested wearing fabric gloves under cleanroom gloves for thermal protection during prolonged duration processing with the solvent.

The shop at SSC was noted to have two main engineering technicians cleaning between 25 and 40 parts per week; parts consisted of mostly transducers, gauges, and other small items. Most parts are utilized for liquid hydrogen and liquid oxygen systems; no hydrazine or NTO/MON system parts are cleaned by their facility. The conversion to Solstice PF at the facility was stated to have minimal issues, and be beneficial in being able to eliminate use of solvent pumps due to the pressurized cylinders in use.

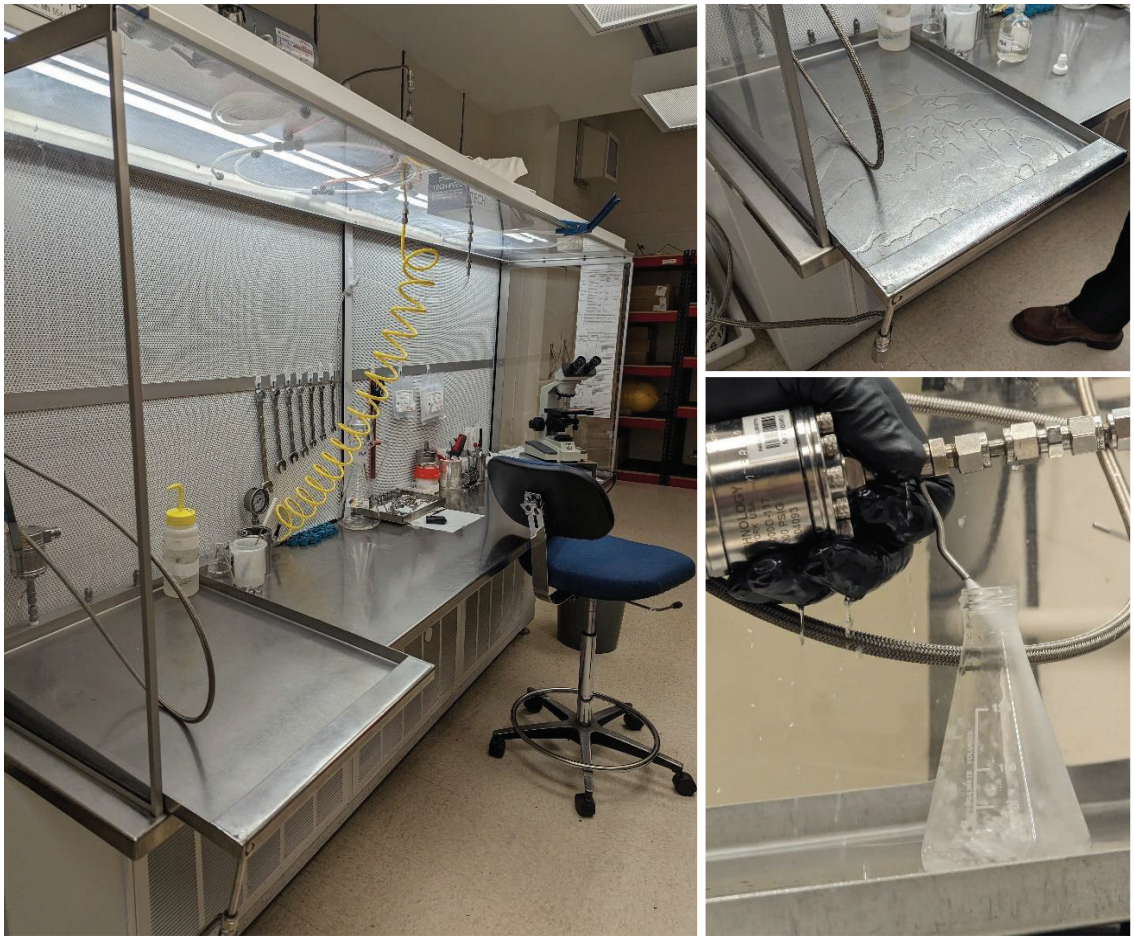


Figure 3. SSC Laboratory/Shop Laminar Bench Station (left), Angled Excess Solstice PF Collection Tray (top right), and Transducer Processing Sample Collection Demonstration (bottom right)

7.1.2.2 Michoud Assembly Facility Visit, June 2023

Representatives from KSC and the NESC also met with the Technician Supervisor for the MAF Component Processing Facility to compare adoption and implementation of Solstice PF at the facility to that at SSC.

Solstice Use

MAF utilizes 200-pound cylinders of the HP-grade Solstice. Occasionally, the non-HP grade will be purchased if HP grade is not available. When using the non-HP grade, NVR testing of the cylinder is carried out; if NVR passes their specification, it is used as is, and if it fails, MAF has the capability to refine the solvent to necessary NVR levels. Similar to SSC, MAF maintains a nitrogen head pressure (~30 - 40 psi) on the cylinders to allow for adequate flow during cleaning. Estimated annual consumption was 1,500 - 2,000 pounds (e.g., 8 - 10 cylinders).

Cleaning Volume and Laboratory/Shop Setup

The MAF cleaning facility is situated in a larger, warehouse-style-area of the building and is responsible for the cleaning of large parts supporting operations at MAF and SSC. The shop processes between 80 and 100 components per month, including valves, pipes, hoses, and fittings that support the engine test stands at SSC (MAF processes ground service equipment, not flight items). Processing tanks are used for precleaning and treatment of components (e.g., caustic, nitric acid, Brulin, phosphoric acid, and rust preventative baths) similar to that at KSC-CRCA, but tailored for larger components. Solstice, legacy HCFC-225 stocks, and demineralized water are used for validation of cleanliness. The shop also has an International Standards Organization (ISO) Class 7 cleanroom for processing components, and can clean to levels as low as level 50A [153]. NVR is tested every day there is a plan to utilize the solvent for cleaning components.

A designated footprint for processing of parts with Solstice PF was within the component-cleaning shop area. A dedicated ‘clean’ and ‘dirty’ cylinder are kept in a refrigeration unit, controlled to 45 °F, to help minimize volatilization and loss (Figure 4). The refrigerated cylinders sit on scales to verify volume during processing and are not exchanged due to difficulty in moving and positioning. Additional clean/stock cylinders and dedicated dirty cylinders are used to fill and empty the respective refrigerated tanks.

Figure 4. Clean (Right, Blue) and Dirty/Collection (Left, Yellow) Solstice cylinders in refrigeration unit at MAF Cleaning Facility

The plumbing and cylinder set up function as a closed-system providing single direction flow-through cleaning of components (e.g., hoses) where the clean tank is connected to the component, solvent is flowed through, and then collected in the dirty tank. Small spray canisters are also used for spray-down of parts as needed. The process solvent loss is estimated at 40%.

With capture of the dirty solvent, MAF utilizes a Kyzen Solstice Distillation System onsite (Figure 5) to recover and reuse spent solvent. The system houses a 30-gallon dirty tank and 30-gallon clean tank; the clean tank is refrigerated and can store solvent, though it is not suggested because any loss of power will cause loss of that volume. The system is capable of processing 8 gallons of Solstice per hour. Not only can MAF distill and reuse processed solvent, but they can further purify the non-HP grade product if initial NVR levels are unacceptable or distill and reset the shelf life of the HP-grade product (4 years) if needed.

Figure 5. Kyzen Solstice Distillation System at MAF

7.1.3 Other Cleaning Institutions Across the Agency

7.1.3.1 KSC-CRCA

Solvent Use

Currently KSC's Component Refurbishment Shop utilizes three different solvents in their precision cleaning processes: HFE-7100, Vertrel™ MCA (used as part of a dual solvent method with HFE-7100), and IPA. The solvent type utilized is dependent on component service fluid type and/or customer preference. The consumption level for HFE-7100 is approximately three to four 55-gallon drums per month with recovery and recycling of the fluid (solvent loss from process and distillation is estimated at ~20%), for Vertrel MCA is around one 55-gallon drum per month with recovery and recycling of the fluid (solvent loss from processing and distillation is estimated at ~20%); and for IPA, is approximately six to eight 55-gallon drums (no recovery and recycling).

Cleaning Volume and Shop Setup

The KSC Component Refurbishment Shop provides decontamination of hypergolic system components, surface treatments (e.g., passivation, pickling, etc.), hydraulic and pneumatic functional testing, refurbishment of functional components to like-new condition, and precision cleaning (in-house, in a clean room environment, and limited in-field services) for a wide range of components for both ground and flight hardware that supports NASA programs and commercial partner space programs. The shop consists of ~15,000 sq. ft. dedicated to engineering, rough/pre-cleaning, chemical treatment baths, quality lab, and the IPA processing

area; a ~5,000-sq.-ft. ISO Class 5 cleanroom for precision cleaning/assembly/packaging of components and relief valve testing; additional outdoor field cleaning areas for larger components (e.g., large diameter/long hoses, compressed gas trailers, large transfer tanks, etc.); and decontamination facility for hypergolic component processing. For HFE-7100, specifically, there is a dedicated area within the clean room with a custom-plumbed sink providing capability for submerging, flowing through, and rinsing components with the solvent. This allows for sampling of the rinse for cleanliness verification and recapture to a holding tank for distillation and reuse.

The department comprises more than 40 employees, including cleaning technicians, engineers, and quality assurance technicians. Processing, on average, consists of approximately 650 work orders per month; a work order can be for a single component of varied complexity (e.g., an accumulator, full system panel, regulator, etc.) or up to 50 identical fittings (Figure 6). Components submitted to the shop are for all commodities in use at KSC including gases (e.g., nitrogen, air, oxygen, helium, hydrogen, etc.), cryogens (e.g., liquid nitrogen, liquid oxygen, liquid hydrogen, etc.), solvents, water, hydraulic fluids, and hypergolic commodities (e.g., hydrazine, monomethylhydrazine, nitrogen tetroxide), etc.

Maximum Quantity Limits to be Submitted on a Single Form

Accumulators 1	Hoses, Vacuum Jacketed 1	Systems ("in-place" cleaning and/or decontamination)
Back-to-Backs 15	Hoses, Flexible (not convoluted)	..... Contact Component Refurbishment Supervisor
Burst Discs 1	Short - up to 1/2" x 10' 5	Tubing (hardlines)
Cylinders 1	Short - 1/2" to 1" x 10' 3	Short - up to 1/2" x 6' 10
Drums 1	Short - over 1" dia. up to 10' 1	Medium - over 1/2" x 6' to 10' 5
Filter Assemblies 1	Medium - up to 1" dia., 10' to 20' 3	Large - over 1/2" and over 10' 1
Filter Elements (not assemblies)	Medium - over 1" dia., 10' to 20' 1	Valves (except Solenoid Valves)
Small - up to 1/2" x 6" 5	Long - any dia., over 20' 1	Small Ports - up to 3/4" port 5
Large - over 1/2" x 6" 1	Millipore Filter Holders 5	Large Ports - over 3/4" port 1
Fittings	Panels 1	Valves, Solenoid 1
Assorted 20	Probes 1	
Identical 50	Q.D. Assemblies 1	Note: any components not defined in the preceding are rto be listed as:
Flanges 2	Regulators 1	
Gages 2	Soft Goods	Miscellaneous
Glassware 5	Small - up to 1" 50	Functional 1
Hoses, Convoluted	Medium - 1" to 4" 10	Non-Functional 5
Small - up to 3/4" dia., any length 2	Large - over 4" 5	
Large - over 3/4" dia., any length 1		

Figure 6. KSC-CRCA Work Order Component Quantity Limits

7.1.3.2 JSC Cleaning Shop, August 2024

Representatives from KSC visited the JSC Cleaning Facility to understand current precision cleaning techniques and systems in place to support JSC facilities and programs. The JSC shop experiences highly variable workloads that are dependent on payload schedules. On average, the shop cleans thousands of individual parts annually; most of the incoming work is for smaller-scale items (fittings, soft goods, facilities equipment, parts for small payloads/cubesats, etc.) with the JSC Crew and Thermal Systems Division being the largest customer. No engineering support is available in the shop — only two cleaning technicians. The shop has deionized (DI) water and aqueous detergent sonication for precleaning, as well as a suite of passivation/surface treatment baths (Figure 7). Final rinse and validation are carried out with a Solvac Vapor Degreasing System using HFE-7100 in an ISO Class 6 cleanroom (Figure 8). The system is tunable to allow for the use of Solstice in addition to HFE-7100; and possibly other alternative solvents within its operating range.

Figure 7. JSC Cleaning Shop Aqueous Ultrasonic Baths (Left) and Pre-Clean/Passivation Tanks (Right)

Figure 8. JSC Cleaning Shop Vapor Degreasing System and ISO Class 6 Cleanroom Area

The JSC Precision Cleaning Shop also has two distillation systems for solvent recovery. The first is a 28-gallon heritage still specifically for HFE-7100; and the second is a brand new tunable system (Figure 9) equipped to reclaim HFE-7100, Solstice, and other solvents, if desired, including flammable solvents. The system is capable of processing approximately 15 gallons of solvent per hour with 500-gallon dirty and clean tank capacities.

Figure 9. JSC New Solvent Distillation System

7.1.3.3 NBL Cleaning Shop, August 2024

Representatives from KSC visited the JSC Neutral Buoyancy Laboratory (NBL) to understand current precision cleaning techniques and systems in place for the facility. The NBL has its own cleaning shop separate from JSC for servicing critical equipment (e.g., tanks, fittings, regulators, manifolds, etc.) used by the dive staff and astronauts. The cleaning team consists of a Lead and two technicians for servicing in-house self-contained underwater breathing apparatus (SCUBA) gear and two additional technicians that help support cleaning of additional equipment and external activities. Aqueous cleaning using a surfactant degreaser and IPA are used for precleaning and adhesive removal requirements; passivation is also carried out for parts going into the pool. Final rinse and precision cleaning utilizes a vapor degreaser system by Solvac (Figure 10) with HFE-7100; nominal requirements for precision cleaning are to meet level 300A, per JSC and Institute of Environmental Sciences and Technology (IEST) specifications, though the shop can also clean to level 100 and 150 if required. The shop has also outfitted the degreasing system with a pressure wand to allow for flow through cleaning or rinsing if needed for specific parts cleaning. The current consumption rate for HFE-7100 is estimated at four to five 55-gallon drums per year.

Figure 10. NBL Vapor Degreasing System

7.1.3.4 MSFC Valve and Component Laboratory, April 2024

Representatives from KSC visited the MSFC Valve and Component Laboratory to examine current precision cleaning techniques and systems in place for the center's operational and programmatic cleaning needs. The shop is comprised of one laboratory technician and five to six mechanical technicians. Shop workload and solvent usage are highly variable depending on test stand and other work occurring at MSFC. A Detrex Corporation Vapor Degreasing System (Figure 11), originally designed for use of Freon 113, adapted to use HFE-7100, and now adapted to use Solstice is the workhorse for the shop. Solstice consumption ranges around 20 - 30 lbs. per week when the system is operating optimally; however, because the system is not optimized and specially designed for Solstice, the usage can be much higher.

Figure 11. MSFC Valve Shop Vapor Degreaser

7.1.3.5 WSTF Cleaning Services Shop, March 2025

Representatives from KSC visited the WSTF Cleaning Services Shop to understand current precision cleaning techniques and systems in use. WSTF Cleaning Services comprise five to seven technicians supporting precision cleaning activities, with additional valve shop technicians who routinely interface with the shop. Precleaning procedures include use of aqueous detergent ultrasonic bath, impingement, and scrubbing techniques, as well as passivation treatments where required. The department has a Class 100 and 10k Cleanroom Area and HFE-7100 solvent cleaning is achieved with a Baron-Blakeslee Vapor Degreasing System (Figure 12). It is estimated that the shop consumes approximately four 55-gallon drums of HFE-7100 and processes approximately 450 cleaning orders (can be a single part or multiple parts) annually, with the majority of requests requiring a 300A cleanliness level per JSC or IEST specifications.

Figure 12. WSTF Cleaning Services Shop: Aqueous Detergent Ultrasonic Baths (Top Left), HFE-7100 Vapor Degreasing System (Top Right), and Precision Cleaning Processing Area (Bottom)

7.1.4 Solstice PF Successes, Limitations, and Use Considerations

After reviewing the implementation process at SSC and MAF, it is clear that cases exist where adoption of Solstice PF/PF-HP for precision cleaning and cleanliness verification is feasible. Smaller cleaning and cleanliness verification operations on a similar scale to SSC and MAF may be able to adopt similar setups with minimal modifications, allowing for a near-term solvent solution that has already been through considerable testing, validation, and verification. For larger throughput operations (e.g., KSC-CRCA) or those utilizing vapor degreasers designed around HFE-7100 requirements (e.g., NBL, WSTF, MSFC), the significantly different physical properties between Solstice PF and HFE-7100 along with the perceived loss during processing, make adoption of the solvent for use likely financially impractical.

A single, standalone cleaning station designed for Solstice PF use where there is a cleaning basin within a clean room area and plumbing to a maintenance skid (consisting of a 20-gallon clean storage tank, 20-gallon dirty collection tank, and integrated distillation to recover and recycle solvent not lost to atmosphere during processing) would cost approximately $200,000. This would serve as a single station for cleaning; multiple units may be required based on throughput requirements (e.g., KSC-CRCA estimates a need of at least four or five to accommodate nominal processing levels within the clean room alone). The current sizing quoted would also likely require frequent recharging of Solstice PF due to processing loss and/or wait times while the solvent distillation process progresses dependent on the distillation rate of the system. These limitations would likely lead to significant loss in productivity for the shop. Discussion with the company on larger systems and throughput capability significantly increased pricing of the system. Further, these cleaning stations do not address flow through cleaning of larger diameter, long hoses, and other field cleaning requirements that would need a supplementary processing option such as the closed loop process and corresponding distillation system at MAF, leading to additional costs.

Utilization of larger cylinders like SSC and MAF have implemented, may lead to significant facility modifications of insulated solvent lines, addition of nitrogen gas drops, changes to or replacement of current HFE-7100 processing sinks to accommodate addition of a head pressure on the solvent, recapture of solvent, possible cooling or refrigeration of the tank storage area to minimize loss would incur costs that are financially irresponsible to execute in the facility. A distillation system similar to what MAF has in place (possibly larger or multiple to accommodate timely distillation based on the throughput capacity) would also be required for higher throughput facilities.

An additional consideration to make in such a drastic change to the large facility is the ability to easily convert to an alternate solvent should the need arise (e.g., availability issues for the commodity, future possible restriction of the commodity, etc.). The majority of other HFE-7100 replacement solvents under consideration as a near-term replacement solution are closer in physical properties that should allow for easier exchange without major modifications or purchase of completely new processing equipment. Additional target goals for this assessment focused on the identification of novel technologies for the minimization or elimination of solvents at risk of targeted future regulation/restriction. These novel technologies will likely require considerable capital for implementation within the next several years. By looking for a near-term option that minimizes current costs to hold cleaning capability in a status quo while these technologies are developed rather than require a large investment for a near-term AND

more permanent solution would be a more worthwhile endeavor for Agency facilities, especially when considering larger, high throughput processing facilities.

7.2 Task 1B: Evaluation of 'Drop-In' Replacement Candidates for Novec HFE-7100

7.2.1 Requirements and Desired Properties for Candidates

When sourcing candidates for laboratory screening to replace HFE-7100, a number of key properties were identified as desirable, as well as several key requirements:

- Solvent Baseline NVR: For precision cleaning, an inherently low background NVR in the selected solvent is necessary. HFE-7100 is advertised to have a maximum of 2 ppmw (3 mg/L) from 3M. A majority of specifications currently in use for Agency programs require the maximum allowable NVR to cover a range of 1.0 ppmw (1.5 mg/L) to 10 ppmw (15 mg/L) at procurement and a range of 3.3 ppmw (5 mg/L) to 10 ppmw (15 mg/L) at "as delivered to interface" [14, 15, 16, 17, 18]. Replacement candidates are expected to have similar requirements levied.
- Boiling Point (BP): Many systems and processes currently in place at Agency precision cleaning facilities were developed around the specific physical properties of HFE-7100. In an effort to minimize capital expense on system modifications for a near-term solution, it is desirable to have a candidate with close or slightly higher BP to HFE-7100.
- Vapor Pressure (VP): As discussed with BP, candidates with a similar vapor pressure are more desirable for cleaning facilities utilizing vapor degreasing as many systems are not tunable to extremely different set points to avoid major capital expenses in adoption of a new solvent. Similar or slightly lower vapor pressures help to minimize evaporation during all types of cleaning processes.
- Surface Tension/Wettability: Surface tension and wettability are closely related properties that can have implications for the cleaning efficiency of solvents. While surface tension is the force that causes liquids to minimize their surface area, wettability refers to how well a liquid spreads out on a solid surface. Generally, lower surface tension liquids tend to have better wettability, though wettability also depends on the solid with which the liquid is interacting. Wetting index can be calculated as follows: [1000*density (g/mL)]/[Surface Tension (dyne/cm)*Viscosity (cP)].
- Kauri-Butanol (Kb) Value: The Kb value is a standardized measure of solvent power for a hydrocarbon solvent. A higher Kb value means the solvent is more aggressive in its ability to dissolve certain materials; it can range from very mild (value of ~10) to very strong (value of 200 or more). Selection of a solvent with a Kb value tailored to the contamination being removed is important in solvent choice. HFE-7100 is considered a mild solvent with its Kb value of 10; a higher Kb value would be desired for more effective removal of complex contaminants, but can come at a cost of materials compatibility, specifically with plastics.
- Flashpoint/Flammability: One of the critical reasons for an HFE-7100 replacement is the need for a non-flammable, oxygen-compatible solvent as HFE-7100 is the current sole approved solvent for oxygen system hardware in multiple specifications documents. While there have been ongoing discussions on adopting a solvent with a flammability rating as a

cleaner as long as it can be shown that no residual remains in the system, the majority of system owners remain uncomfortable with the associated risk when nonflammable options still exist.

- Safety and Industrial Hygiene Guidelines: Not only do the properties associated with the cleaning efficiency play a role in the selection of candidate solvents, but safety considerations are also important in final selections for nominal processing and handling during cleaning activities. Exposure guidelines (e.g., 8-hr Time Weighted Average (TWA), Ceiling Exposure Limit, etc.) should be considered for possible facility or operational changes would need to be implemented with the new candidate. This could lead to significant changes in ventilation requirements, a need to wear respirators, and/or changes in personal protective equipment compared to the status quo of HFE-7100.

7.2.2 Survey of Commercially Available Options

A broad survey of commercially available solvent options was completed. Upon initial investigation, there appeared to be a large number of candidates available. As discussions with various vendors progressed, it was determined that many options were actually the same source product repackaged with a new name specific to the distributing vendor, with much fewer unique options. Based on the survey, the candidates in Table 3 were selected for testing; there are two groups – those not containing trans-dichloroethylene (tDCE) and those that do. Extended properties for each of the candidates listed is also included in Table 4.

Table 3. Novec HFE-7100 Replacement Candidates

Product Name	Vendor	Product Details
Non-tDCE Containing Candidates		
Promosolv DR3	Inventec Performance Chemicals	Molecularly Equivalent to Novec HFE-7100 used as surrogate after initial analysis showed equivalency
BestSolv Sierra	Best Technologies	Proprietary Fluorinated Multiple vendors offer equivalent product
Ensolv Fluoro IC	Enviro-Tech	Equivalent to Novec 649 Heptafluoroisopropylpentafluoroethyl ketone (CAS 756-13-8)
Opteon SF33	Chemours	HFO-1336mzz-Z (Z)-1,1,1,4,4,4-Hexafluoro-2-butene (CAS 692-49-9)
Amolea AS-300	AGC	1-Chloro-2,3,3-trifluoropropene (>89% Z isomer/<10% E isomer, CAS 1263679-68-0) Contains stabilizer (<1%, Trade Secret)
Aerotron CE	Reliance	Proprietary Fluorinated Hydrofluoroether (>90%) Contains additives (<10%)
HFE HP-HFMOP	Halocarbon	1,1,1,3,3,3-Hexafluoro-2-methoxypropane (HFE-356mmz1, CAS 13171-18-1) *Added late in assessment – limited testing completed
tDCE Containing Candidates		
Vertrel MCA		Decafluoropropane (62%, CAS 138495-42-8)/tDCE (38%) Mix Currently utilized in dual solvent system with HFE-7100 used as comparator to other tDCE-containing candidates for certain tests
Opteon SF30	Chemours	Opteon SF33/tDCE (20-30%) Mix

Product Name	Vendor	Product Details
Amolea AS-300 AT	AGC	AS-300/tDCE (60-70%) Azeotrope Mix
Aerotron 100	Reliance	Aerotron CE (<40%)/tDCE (>55%) Mix Contains additives (<5.0%)
Aerotron AV	Reliance	Aerotron 100 Contains additional additives; Aviation blend

Table 4. HFE-7100 Replacement Candidate Properties

Property	Novec HFE-7100 / Promosolv DR3	BestSolv Sierra	Ensolv Fluoro IC	Opteon SF33	Amolea AS-300	Aerotron CE	HFE HP-HFMOP	Vertrel MCA	Opteon SF30	Amolea AS-300 AT	Aeroteon 100 / AV
Molecular Weight (g/mol)	250	200	316	164	130.5	200	182	Mix	Mix	Mix	Mix
Boiling Point (°C)	61	56	49	33	54	54	51	39	29.1	47	47
Freezing Point (°C)	-135	-93	-108	-107	-116	-86	<-78	<-50	<-80		<-50
Liquid Density at 25°C (g/mL)	1.52	1.47	1.6	1.36	1.39	1.47	1.39	1.41	1.33	1.28	1.28
Vapor Pressure at 25 °C (kPa)	26.9	31	40.4	70	32	28	36.1	61.9	86.3	45.5	52.7
Liquid Viscosity at 25 °C (cP)	0.61	0.65	0.56	0.38	0.57	0.43	0.33	0.49	0.33	0.42	0.49
Surface Tension at 25 °C (dyne/cm)	13.6	16.4	11.4	13	21.7	16.3	15.1	15.2	16.4	22	19.5
Latent Heat of Vaporization at Boiling Point (kJ/kg)	112	163	88	166	213	230	172	180			280
Kb Value	10	13		11.3	44	45	9.73	25	20	118	93
Wetting Index	183	138	250	275	112	210	279	189	246	139	134
Flash Point		None	None	None	None	None	None	None	None	None	None
Flammable/Explosive Limits, LEL-UEL (% vol)	None	None	None	None	7-14	None	Not Applicable	None	None	7.3-16.5	7-14
Occupational Exposure Limit, OEL, 8-hr Time Weighted Average (ppm)	750	No OSHA PEL published; 50 ppm manufacturers' recommendation	No OSHA PEL published; 150 ppm manufacturers' recommendation	500	250	50	No OSHA PEL published	200	200	200	No OSHA PEL published; 150 ppm manufacturers' recommendation
Ozone Depletion Potential, ODP	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00	0.00
Global Warming Potential, GWP (100-year)	320	540	≤1	2	<1		27	806		<1	

7.2.3 Baseline NVR for Candidates

As mentioned, an inherently low background NVR in the selected solvent is necessary for precision cleaning to ensure no new residue is introduced to a system or component during the cleaning process. To assess the baseline gravimetric NVR in HFE-7100 replacement candidates, 100-mL aliquots were evaporated at a temperature slightly below the solvent's BP in pre-weighed aluminum pans. After all liquid was evaporated, the pans with remaining residue were dried in an oven at 70 °C for 1 hour, moved to a room temperature desiccator for 1 hour, and then reweighed. The resulting mass of residue per 100 mL was normalized to mg residue per 1 L of solvent. Testing was completed in triplicate; average results with standard deviation are presented in Figure 13.

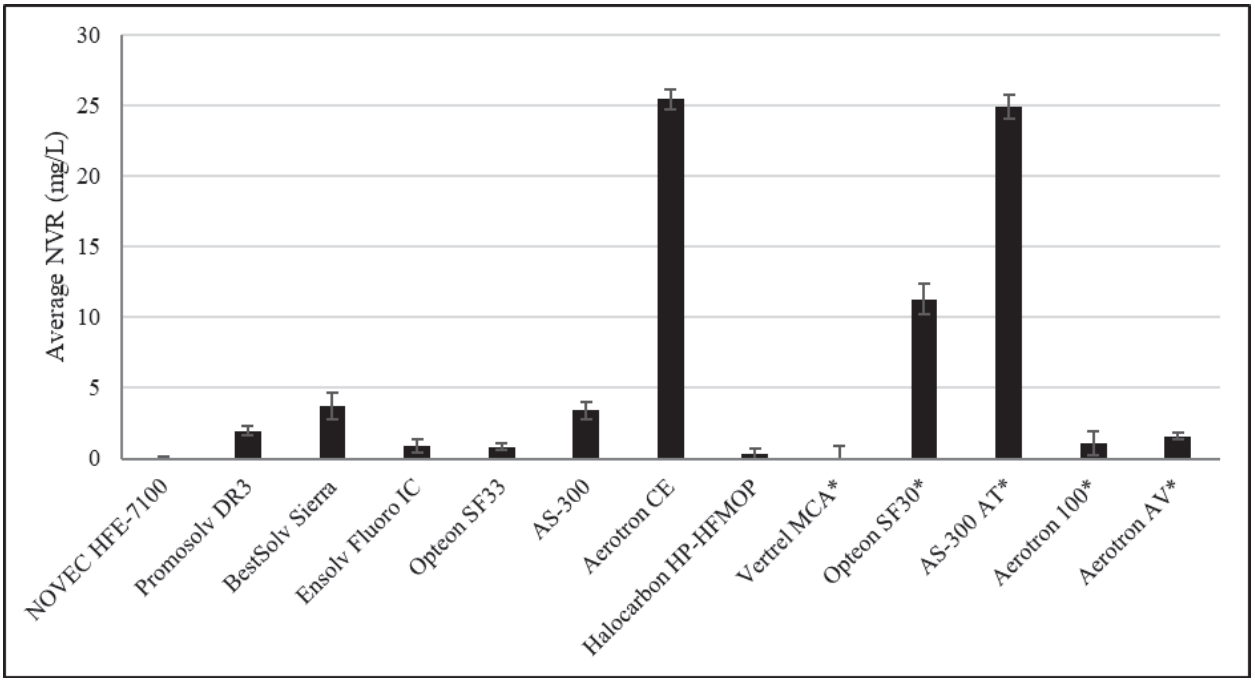
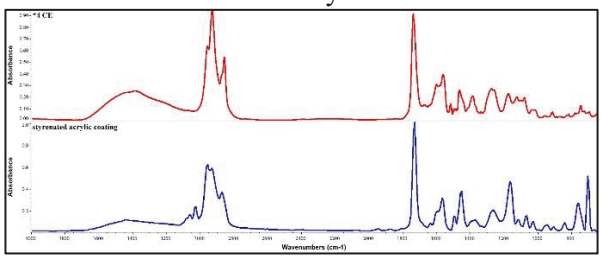
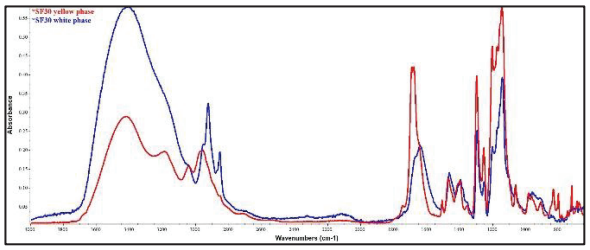
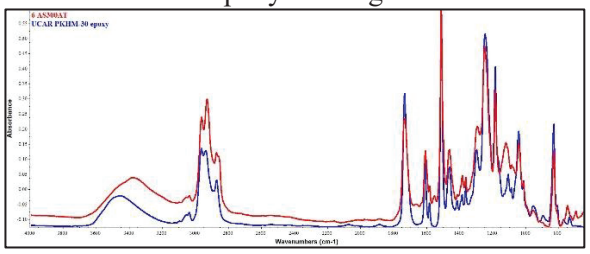


Figure 13. Average Baseline NVR in HFE-7100 Replacement Candidates. An asterisk (*) designates that the solvent contains tDCE (errors bars represent the standard deviation).

Based on requirements for procurement and "as delivered to interface" for the specifications mentioned in Section 7.2.1, a threshold minimum passing baseline NVR was set at 10 mg/L. All but three of the candidates met this requirement with average baseline NVR levels below 5 mg/L. For the three candidates failing the threshold of 10 mg/L, the residues were analyzed by Fourier Transform Infrared (FTIR) spectroscopy; resulting residue identifications, notated sources, and purification options are presented in Table 5.

Table 5. High NVR Identification Results

Solvent	Residue Identification and FTIR Spectra	Notes
Aerotron CE	Possible Alkyd Resin 	Material exhibited aromatic, aliphatic, and ester functionalities. Spectral comparison with a styrenated acrylic (commonly used resin in paints/coatings) is shown to the left. Reliance Chemicals verified that they do have the ability to further purity to a requirement of <10 mg/L (likely additional cost)
Opteon SF30	Unidentified 	Two phases (white and yellow) noted that closely resembled each other; the white residue exhibited aliphatic hydrocarbon, secondary or tertiary alcohol, and doubly unsaturated or mixed ether functionalities. The yellow residue was similar to the white with addition of a possible amide. Source likely resulting from tDCE leaching a material from a container coating or direct impurity in tDCE used in mix as high residue was not noted in SF33.
AS-300 AT	Epoxy Coating 	Source likely epoxy phenolic coating from the container. It was noted from AGC Chemicals that higher NVR tends to be seen in their smaller package sizes and are possibly related to the surface container area versus solvent volume. Further purification may be limited by residue limit allowed in tDCE at time of procurement and would likely incur additional cost. Container change may help eliminate the problem.

7.2.4 Hydrocarbon Miscibility and Down Selection #1

It has been seen in previous solvent studies [1] that in testing with high concentrations of contaminants, particularly those that are hydrocarbon based, they can separate out from the cleaning solvent when the solvent has a perfluorinated chemistry. This separation is not a desired trait of the solvent; for acceptable removal of contaminants the goal is to have them solubilized. Quick screening of the solubility and miscibility for common hydrocarbon contaminants was performed. The contaminants tested were RP-1 petroleum-based rocket propellant, MIL-PRF-83282D hydraulic fluid [19], and heavy molecular weight (85-140W) petroleum-based gear oil. 50-µL aliquots of a contaminant were added to 10 mL of solvent candidate until visible phase separation was noted. Figure 14 provides visual results for the testing.

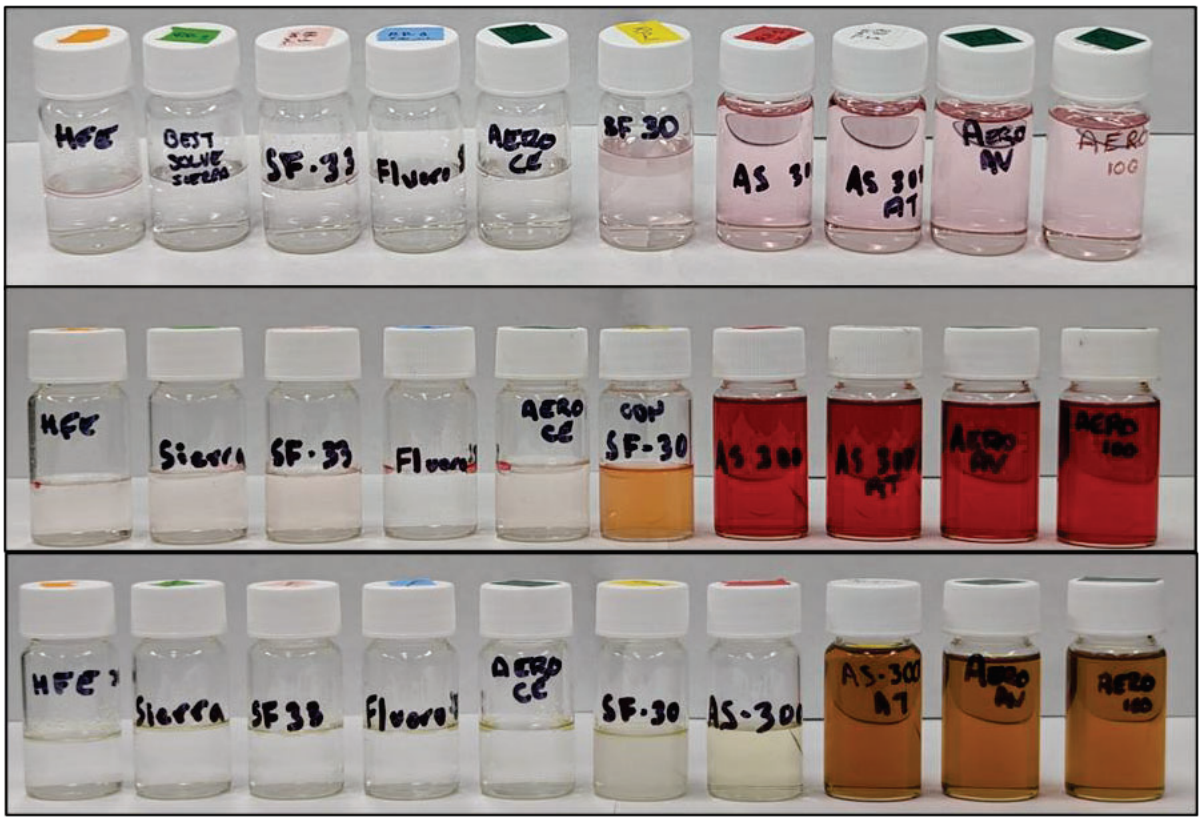


Figure 14. Hydrocarbon Miscibility Tests (Top: RP1 Propellant, Middle: MIL-PRF-83282D Hydraulic Fluid, Bottom: 85-140W Gear Oil). Vials from left to right in each image: HFE-7100, BestSolv Sierra, Opteon SF33, Ensolv Fluoro IC, Aerotron CE, Opteon SF30, Amolea AS-300, Amolea AS-300 AT, Aerotron AV, and Aerotron 100.

A comparison of the concentration ratio of the contaminant to solvent at the point where there was visible phase separation is shown in Figure 15. For non-tDCE-containing solvents other than AS-300, solubility/miscibility was low for all three contaminants. The AS-300 showed full solubility for both RP1 and hydraulic fluid, a significant increase over HFE-7100. While the Opteon SF33 had only moderate improvement over non tDCE-containing solvents, it was on par with Vertrel MCA and the other tDCE-containing candidates showed complete solubility and miscibility for the three contaminants.

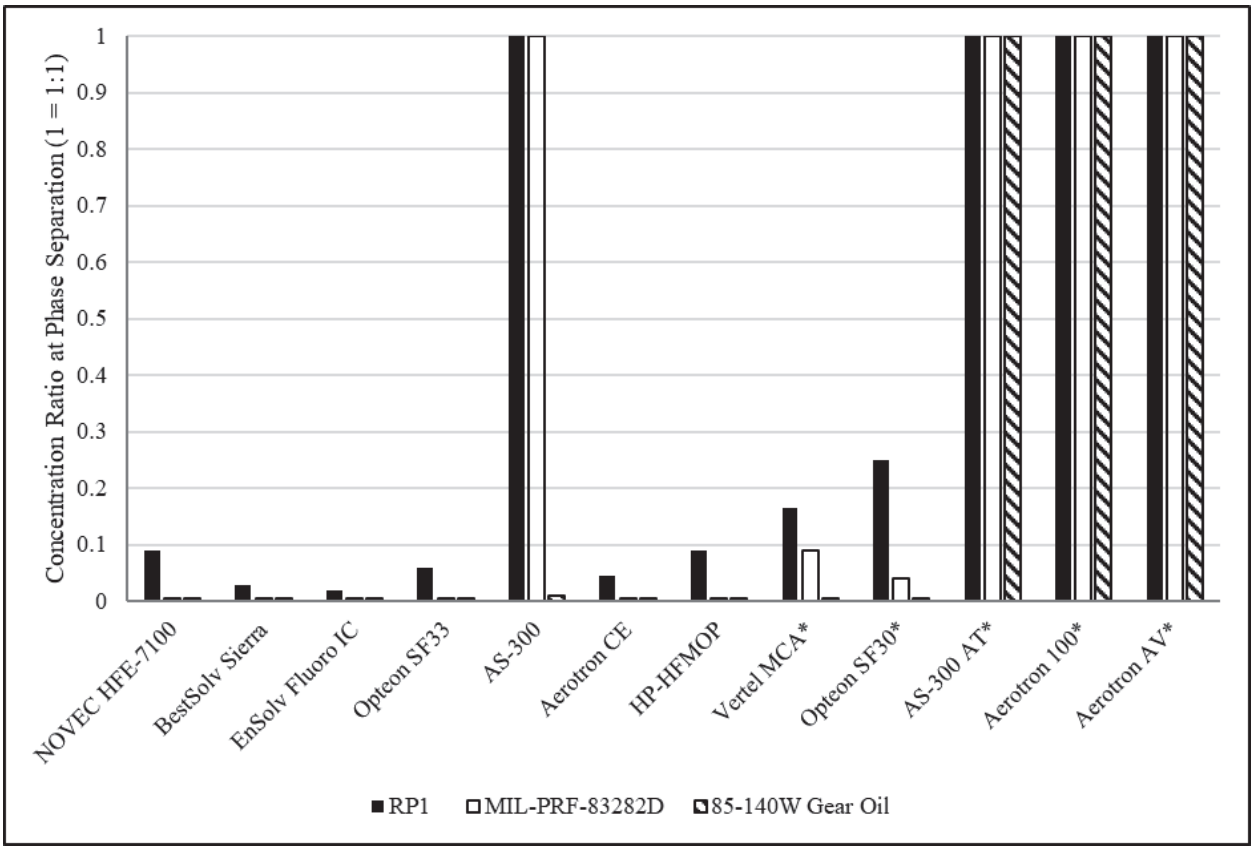


Figure 15. Contaminant to Solvent Concentration Ratio at Point of Visible Phase Separation

With baseline NVR and solvency screening completed, it was determined that the Amolea AS-300 AT would be eliminated from further tested. As it is not a front runner by containing tDCE due to currently slated regulation of the chemical through the TSCA, its non-tDCE-containing counterpart (AS-300) performed very well. Additionally, Aerotron 100 was eliminated from further testing, as Aerotron AV is the same composition with an additional stabilizing additive.

7.2.5 Initial Cleaning Efficacy Testing and Down Selection #2

The next phase of testing included single-contaminant removal challenges to evaluate each solvent's ability to remove a variety of common contaminants expected to be encountered during real-world cleaning of hardware. 70-mm aluminum weigh dishes (~47 cm^2 surface area) were pre-cleaned with Vertrel MCA, allowed to dry, and weighed. Contaminants were solubilized in Vertrel MCA and an aliquot added to the aluminum weigh dish to obtain a target contaminant mass of 3 mg (~43.5 mg/0.1 ft^2). The Vertrel MCA was allowed to evaporate, and the final mass of contaminant was recorded. Each solvent-contaminant combination test was completed in replicates of six.

To test the cleaning efficiency, 33 mL of the candidate solvent was added to a contaminated weigh dish, agitated on an orbital shaker at 60 rpm for 30 seconds, then discarded. This was repeated a total of three times, using 100 mL of candidate solvent per dish. The contaminants tested included: MIL-PRF-83282D hydraulic fluid [19], Light Mineral Oil, Dioctyl sebacate, Braycote 601EF grease, Krytox AC Grease, and Dow Corning silicone vacuum grease.

Removal results for candidates not containing tDCE compared to HFE-7100/Promosolv DR3 are shown in Figure 16. There were a range of results depending on the contaminant family: front runners for hydrocarbon type contaminants were Opteon SF33, Amolea AS-300, and Halocarbon HP-HFMOP. For fluorinated grease removal, Ensolv Fluoro IC, Opteon SF33, and the Halocarbon HP-HFMOP tended to perform similar or better than HFE-7100/Promosolv DR3. Amolea AS-300 was the only candidate that performed well in the removal of silicone grease.

Removal results for candidates containing tDCE are shown in Figure 17. Opteon SF30 performed on par with HFE-7100/Promosolv DR3 and Vertrel MCA across all contaminants examined. Aerotron AV had drastically lower performance for fluorinated grease removal; while it did show improved removal of silicone grease, its lower fluorinated grease removal capacity combined with containing tDCE lowered its ranking in the pool of candidates. It was removed from consideration for the remainder of the tests.

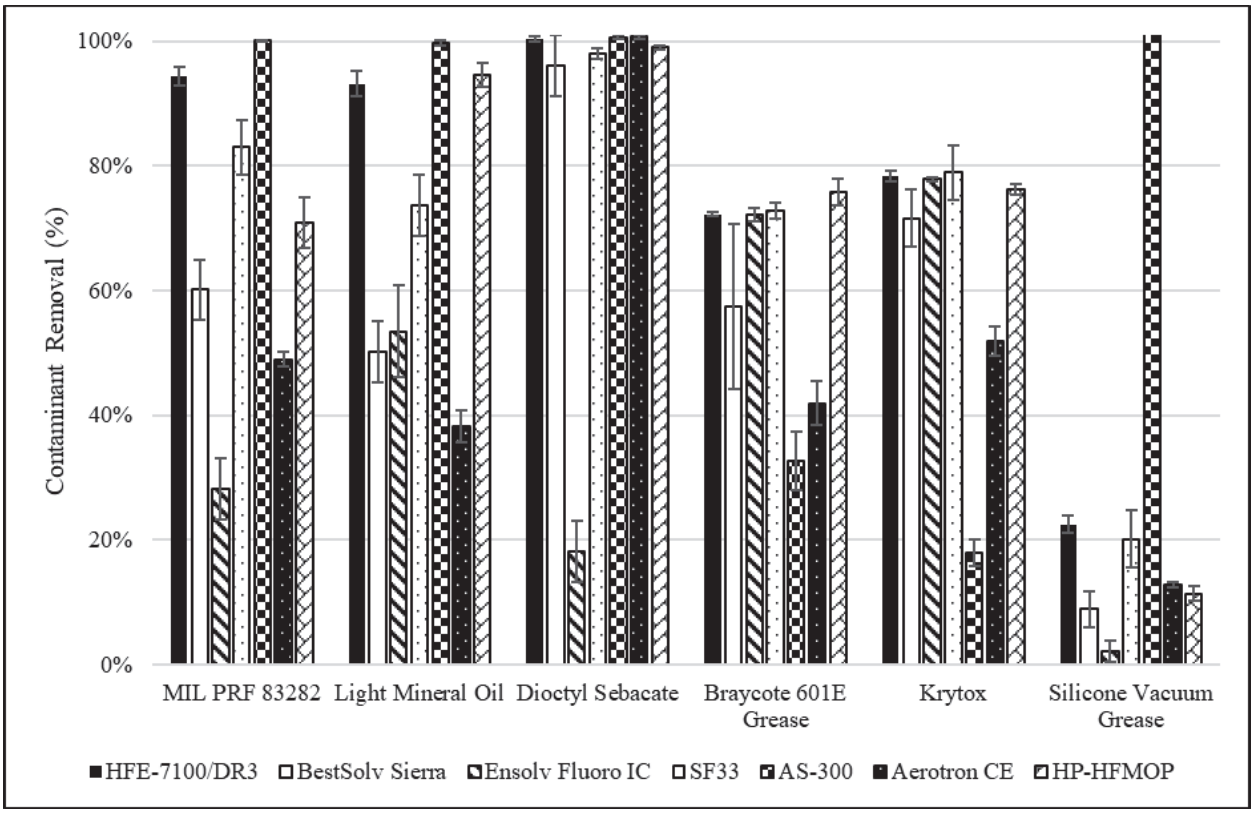


Figure 16. Contaminant Removal Percent for non-tDCE Candidate Solvents (error bars represent the standard deviation)

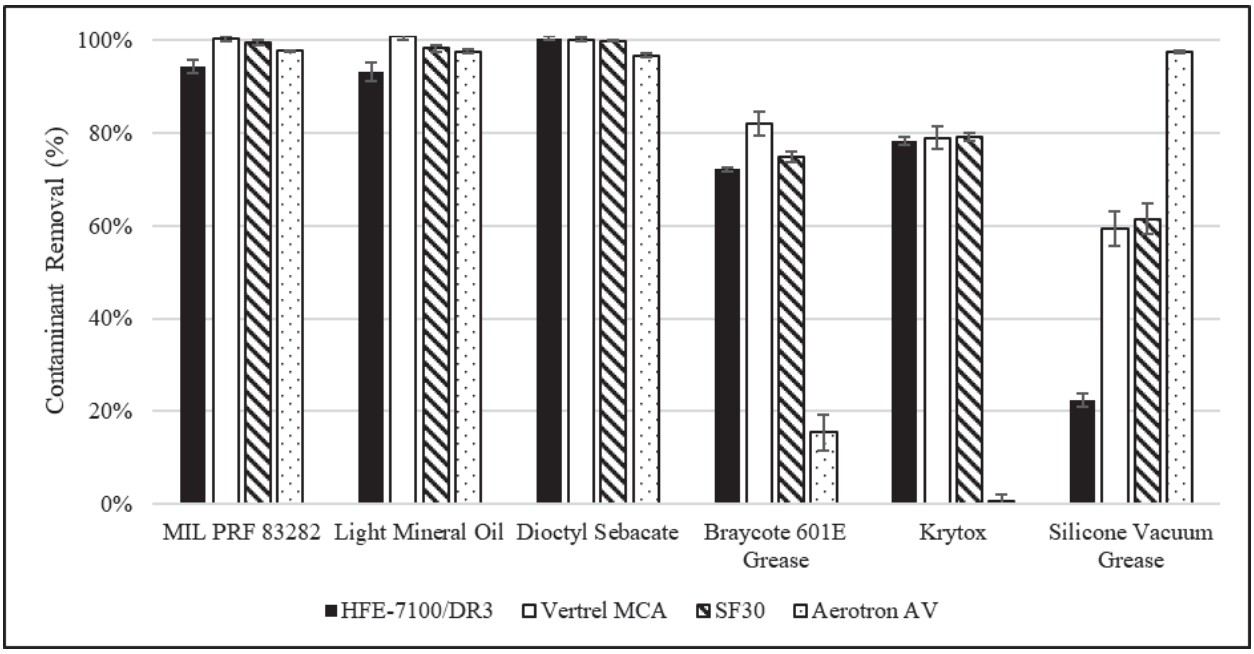


Figure 17. Contaminant Removal Percent for tDCE Candidate Solvents (the error bars represent the standard deviation)

7.2.6 Complex Parts Cleaning and Down Selection #3

The next set of tests examined the cleaning of more complex parts with a mixture of contaminants as closer to 'real world' scenarios for precision cleaning. Parts used in the study included Allan Aircraft 316 Stainless Steel Double Swivel ¼-in SAE Back-to-Back Fittings, Swagelok 316 Stainless Steel 3/8-in Caps, Swagelok 316 Stainless Steel 1/8-in 90-Degree Elbows, and Aluminum 3003-H14 4-in x 4-in Coupons with a 2-in x 2-in section bead-blasted to create a roughened surface, attempting to approximate 600 grit (Figure 18). Parts were chosen to test varied levels of component complexity (with Swivels being more complex) encountered at various cleaning facilities. It is known that cleaning facilities will encounter components much more complex than those tested in this study, however, it was impractical to test larger, more complex items like regulators, valves, etc., in this assessment due to constraints in laboratory testing capability. All parts were sonicated in Vertrel MCA for five minutes, allowed to dry for at least one hour in an oven at 70 °C, brought back to room temperature in a desiccator, then weighed. The process was repeated until stable 'clean' weights were obtained.

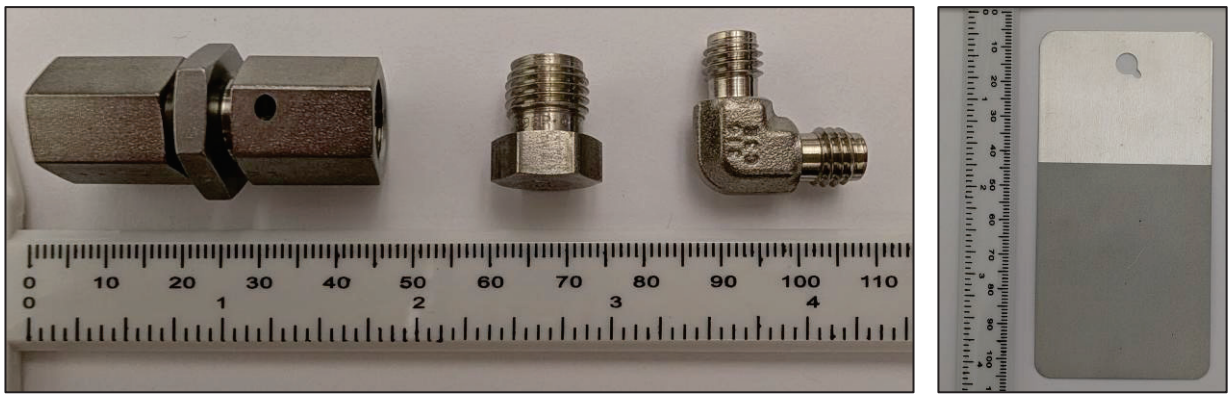


Figure 18. Fittings and Coupons used in Cleaning Efficiency Testing

To contaminate parts, equal amounts (~1.2 g) of Braycote 601EF grease, Krytox 240 AC grease, light mineral oil, MIL-PRF-83282D hydraulic fluid, and dioctyl sebacate were solubilized in 100 mL of Vertrel MCA. Swivel, Cap, and Elbow fittings were dipped into the solution, excess shaken off, and then the solvent allowed to evaporate to leave behind the mixed residue. The roughened area of the coupons was sprayed with the mixture using a Preval Sprayer to produce a uniform residue on their surface. All parts were aged for three weeks in a 70 °C drying oven to produce aged residues similar to what would be seen with real world cleaning applications. Aged contamination levels averaged at ~5 mg/0.1 ft^2 for swivels, ~1.7 mg/0.1 ft^2 for caps, ~2.0 mg/0.1 ft^2 for elbows, and ~50 mg/.1 ft^2 for coupons. Amounts of contaminants were chosen to test the solvents over different levels of contamination with the assumption that most facilities employ a pre-clean process where gross contamination, scale, etc., is removed prior to rinsing and cleanliness verification flushes are performed on components.

Cleaning procedures were carried out for six parts of each type. The cleaning procedure for swivels, caps, and elbows was as follows: For each part type, four beakers containing 250 mL of a candidate solvent in each were set up to provide serial solvent baths. A single part was vigorously, manually agitated for 20 seconds in each successive bath. Excess solvent was shaken off the part, then the part was allowed to dry in a 70 °C oven for at least one hour, allowed to return to room temperature in a desiccator, and weighed. Solvent baths were changed out between each part type. The cleaning procedure for coupons was as follows: The contaminated coupon was suspended; the candidate solvent was loaded into a pressurized sprayer and charged to 80 psi. Each coupon was sprayed from top to bottom for 10 seconds; post-cleaning drying and weighing for the coupons was equivalent to other parts. Percent removal of the mixed contaminant residue (gravimetric) is presented in Figure 19.

The two top non-tDCE-containing solvents across all parts and contamination levels tested were noted to be Amolea AS-300 and Opteon SF33. Amolea AS-300 performed better than Promosolv DR3 (surrogate to/molecularly equivalent to Novec HFE-7100), concurrent with its higher Kb value. SF30 performed approximately the same as DR3 and BestSolv Sierra performed slightly below DR3. Ensolv Fluoro IC and Halocarbon HP-HFMOP had significantly lower performance that would suggest elimination from consideration. Opteon SF33, the only remaining candidate containing tDCE, performed equivalently to Vertrel MCA and as expected, slightly better than Promosolv DR3.

While cleaning efficiency testing provided several clear front runners, other properties of the candidates are presented in Table 6 that should be closely considered as end users review this data. For instance, while BestSolv Sierra is an adequate ‘third place’ candidate in terms of cleaning, it has no established exposure criteria with the manufacturer recommending 50 ppm as the eight-hour TWA. That low concentration level, compared to other candidates, could require significant changes to facility ventilation or require personnel to don respirators if modifications aren’t attainable. Opteon candidates have significantly lower boiling points (thus much higher vapor pressures) which could pose challenges for facilities with flow through style and vapor degreasing style cleaning set ups for evaporative loss of the solvent and overall compatibility with the operation of equipment that may not be tunable. Additionally, as covered in follow on sections of this report, materials compatibility (metals, nonmetals, and oxygen service components) must also be measured in making a decision on a replacement.

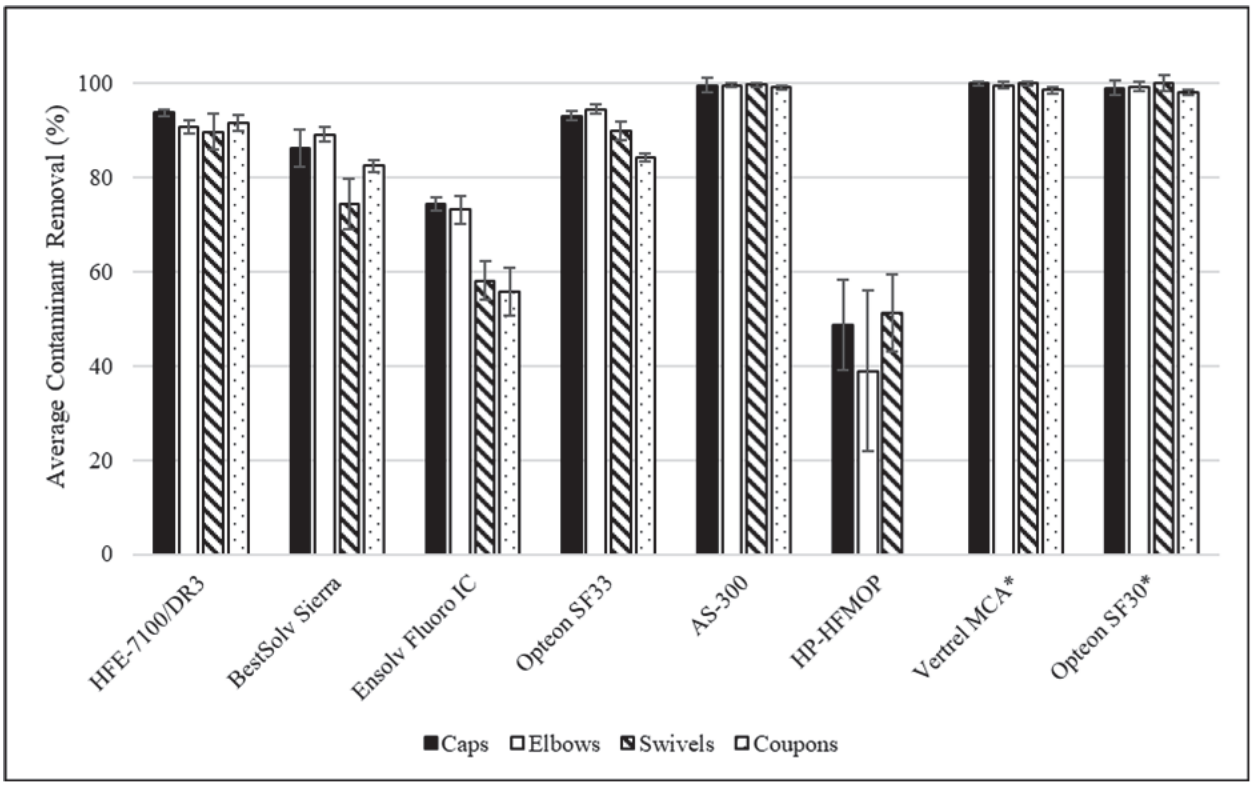


Figure 19. Contaminant Removal from Complex Parts (the error bars represent the standard deviation)

Table 6. Solvent Candidate Selection Considerations

Property	HFE-7100	Amolea AS-300	Opteon SF33	BestSolv Sierra	Opteon SF30
Exposure (8hr TWA, ppm)	750	250	500	None Established by OSHA; Manufacturer recommends 50	500 (fluorinated component); 200 (tDCE)
BP (°C)	61	54	33	56	29
VP (mmHg)	202	240	646	233	525
Liquid Density (g/mL)	1.52	1.39	1.36	1.47	1.33
Kb Factor	10	44	11.3	13	20

7.2.7 Materials Compatibility (Metals, Nonmetals, Oxygen)

7.2.7.1 Metals Compatibility Testing

Common metals used throughout the Agency were tested for compatibility with Promosolv DR3 (again, as the exact molecular equivalent surrogate to Novec HFE-7100), BestSolv Sierra, Ensolv Fluoro IC, Opteon SF33, Amolea AS-300, Vertrel MCA, and Opteon SF30. While noted in Section 7.2.6 that several of these were not top-performing solvents for the mixed contaminant challenge, the compatibility data was still collected to provide reference for end users who may

be interested in their use for a specific cleaning application. The Halocarbon HP-HFMOP solvent was not included in the assessment at the time of this testing.

Coupons were prepared from sheet, bar, or rod stock; computer numerical control (CNC) machining was requested when possible. Material details including stock and sectioning type, if defined by the vendor, are outlined in Table 7. Coupons other than the Titanium (Ti-6Al-4V), Nitronic® 60, and Eligiloy were nominally 0.50-in wide and 3.00-in long with thickness as listed in Table 7, with a 0.25-in diameter hole, and a 600-grit sanded finish. Titanium (Ti-6Al-4V), Eligiloy, and Nitronic were nominally 0.40-in wide and 0.71-in long with thickness as listed in Table 7. 6061-T6 Aluminum coupons were tested as is and with an applied conversion coating (RIE Coatings LLC, Type I, Class 1A per MIL-DTL-5541).

For materials other than Titanium, Nitronic 60, and Eligiloy, exposure testing followed a modified ASTM F483-09 procedure. For full immersion tests, a set of three coupons of the same material, attached to polytetrafluoroethylene (PTFE) spacers to avoid coupons contacting each other for the duration of the test, were placed in heavy wall, glass pressure tubes with enough solvent (50 mL) to completely cover the coupons. For vapor phase tests, the glass tubes were filled with glass Raschig rings to elevate the coupon set above 15 mL of liquid. PTFE plugs with PTFE O-rings were used to seal the tubes. Testing was carried out at or slightly above the boiling point of the solvent to promote a saturated vapor phase and most likely scenario where corrosion might be noted. Testing of Titanium, Nitronic 60, and Eligiloy followed the same line of setup, but as coupons were smaller and had no hole for spacers, each coupon was placed in its own, smaller pressure tube. Full immersion tests used 5 mL of solvent to cover the metal coupon, and vapor phase tests used 5 mL of solvent with Raschig rings to elevate the coupon above the solvent. Examples of the testing set up are shown in Figure 20. All tests were carried out for seven days.

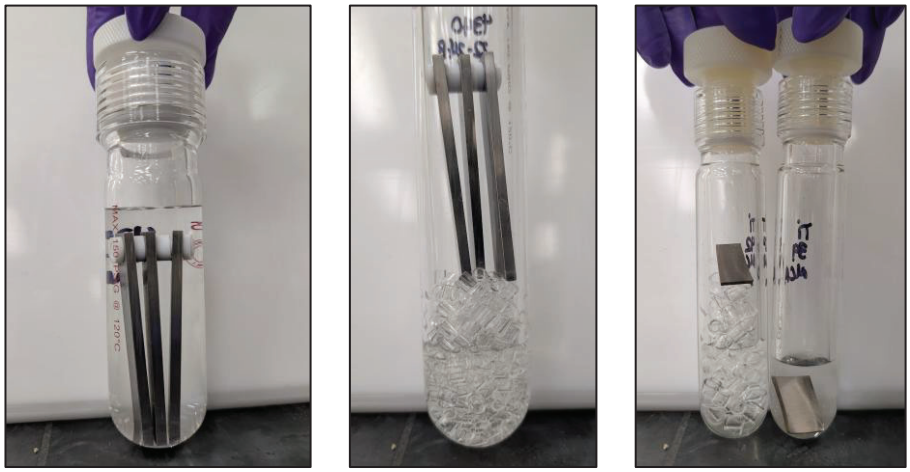


Figure 20. Metal Compatibility Test Setup for Full Immersion Larger Coupons (Left), Vapor Phase Larger Coupons (Middle), and Vapor Phase/Full Immersion Smaller Coupons (Right).

Table 7. Metal Materials for Compatibility Testing

Material (UNS Code)	Vendor (Source)	Lot Information	Nominal Thickness (inches)	Stock and Sectioning Type
15-5PH SS	Metal Samples	Heat: 7250011	0.125	Sheet

Material (UNS Code)	Vendor (Source)	Lot Information	Nominal Thickness (inches)	Stock and Sectioning Type
(S15500)	(AK Steel Corporation)			
440C SS (S44004)	Metal Samples (Admiral Steel)	Heat: N60926	0.125	Sheet
4340 LAS (G43400)	Metal Samples (Cleveland-Cliffs Plate LLC)	Melt: D6601	0.187	Sheet
CDA 443 Brass (C44300)	Metal Samples (Wieland Metal Services West, LLC)	Lot: 09-901341/09-901342 Heat: 166243104	0.062	Sheet
2219-T0 Al (A92219)	Metal Samples (Kaiser Aluminum)	Lot: 334068A4	0.031	Sheet
6061-T6 Al (A96061)	Metal Samples (Henan Mingtai Al. Industrial, Co., Ltd)	Lots: MSH2311W65032, MSH2301W65040	0.062	Sheet
7075-T6 Al (A97075)	Metal Samples (Kaiser Aluminum)	Lots: 113178B8, 451944B3	0.063	Sheet
Inconel 718 (N07718)	Metal Samples (Special Metals)	Heat: HT8854EK/CJ85A	0.063	Sheet
Monel 400 (N04400)	Metal Samples (Special Metals)	Heat: MM39U7BR/SK39N	0.062	Sheet
CDA 102 Cu (C10200)	Metal Samples (Outokumpu Copper)	Lot: VA1001B	0.125	Sheet
Eligiloy (R30003)	Metal Samples (Elgiloy Specialty Metals)	Heat: 129987243(PBE02)	0.062	Bar Laser Cut
Ti-6Al-4V (R56400)	Metal Samples (Perryman Company)	Heat: PVD7505	0.063	Bar EDM Cut (Zucrow Labs/Purdue University)
Nitronic 60 (S21800)	Metal Samples (Fry Steel Company)	Heat: A070914	0.063	Rod CNC cut

Coupons were weighed, high-resolution imaged, and surface roughness analyzed before and after exposure; any visual changes were also noted.

Corrosion was gauged by calculation of mil per year (MPY, g/cm^2). A conservative value of 0.5 g/cm^2 for MPY was set as a failing criterion for compatibility; Table 8 shows samples that failed this MPY criteria. MPY values with a grey background were determined to be statistical outliers (using t-test) from other replicates in their test group. Of the remaining samples that failed, all were 4340 LAS. Full MPY data for all coupons and solvents is presented in Appendix A.

Table 8. Failed MPY Materials for Cleaning Solvents

Material	Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
15-5PH SS	AS-300	9A	I	85.33	8.98
4340 LAS	BestSolv Sierra	13A	I	18.61	1.96

Material	Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
4340 LAS	BestSolv Sierra	14A	I	28.01	2.95
4340 LAS	BestSolv Sierra	16A	V	31.93	3.36
4340 LAS	BestSolv Sierra	17A	V	15.45	1.63
4340 LAS	BestSolv Sierra	18A	V	19.57	2.06
4340 LAS	Fluoro IC	1B	I	28.25	2.97
4340 LAS	Fluoro IC	2B	I	19.79	2.08
4340 LAS	AS-300	9A	I	121.57	12.80
4340 LAS	Opteon SF30	12B	V	29.91	3.15
4340 LAS	Opteon SF30	7B	I	32.07	3.38
4340 LAS	Opteon SF30	8B	I	21.48	2.26
Al 2219	Vertrel MCA	19	I	3.024	1.09
Inconel 718	AS-300	12A	V	186.21	20.40

7.2.7.2 Nonmetals Compatibility Testing

Common nonmetal (soft good) materials used throughout the Agency were tested for compatibility with Promosolv DR3 (again, as the exact molecular equivalent surrogate to Novec HFE-7100), BestSolv Sierra, Ensolv Fluoro IC, Opteon SF33, Amolea AS-300, Vertrel MCA, and Opteon SF30. While noted in Section 7.2.6 that several of these were not top performing solvents for the mixed contaminant challenge, the compatibility data was still collected to provide reference for end users who may be interested in their use for a specific cleaning application. The Halocarbon HP-HFMOP solvent was not included in the assessment at the time of this testing.

Soft goods were purchased as O-ring or gasket configuration; material details are outlined in Table 9. All samples, including controls, were washed with a dilute solution of Liquinox detergent, thoroughly rinsed with high-purity DI water, and allowed to dry completely before initial measurements and testing commenced. Testing was completed for three of each soft good material with specified candidate solvents. Initial mass for the combined lot of three per test was documented. Additionally, initial inner and outer diameter for each individual O-ring/gasket was documented using a Micro Vu Excel 654 UC.

The batches of three of a specified soft good were fully submerged in the candidate fluid for 30 minutes at room temperature then removed from the fluid, dried with a low-linting cellulose task wipe, and placed in a desiccator for 30 minutes. Post-exposure mass and dimensional measurements were then gathered; if the change in mass or thickness exceeded 1%, the samples were placed back into the desiccator and remeasured at the 24-hour mark. If mass and dimensional measurements continued to exceed 1% change from initial values, the samples were again placed in the desiccator and remeasured at the 168-hour mark. All samples underwent hardness, tensile, elongation testing for comparison to unexposed controls either after a <1% change was seen in mass and dimensional measurements or after the 168-hour mark.

Average mass, dimensional, hardness, maximum force, and elongation changes for each material-solvent pair are given in Appendix B. Results are presented with a color scheme of green (<1% change), yellow (≥1%, <10%), and red (≥10%) for each of the characteristics tested as use case for the soft good (e.g., dynamic or static application, etc.) should also be considered by end users when reviewing the data.

Table 9. Nonmetal Materials for Compatibility Testing

Material	Vendor	Lot Information	Details/Form/Nominal Size
Acrylonitrile Butadiene Rubber (Buna N)	McMaster-Carr (Part Number 1307N233)	83311B, 83060A	O-Rings, White, 70A Hardness, 3/32” Fractional Width, 9/16” ID, 3/4” OD
Ethylene Propylene Diene Monomer Rubber (EPDM)	McMaster-Carr (Part Number 9557K224)	0080466561	O-Rings, Black, 70A Hardness, 1/8” Fractional Width, 1/2” ID, 3/4” OD
Ethylene Propylene Rubber (EPR) – EPR-70	Rocket Seals (Part Number 2-011-EPR-70)	N/A	O-Rings, Black, 1-16” Cross Section, 5/16” ID, 7/16” OD
Fluorinated Ethylene Propylene (FEP)	Professional Plastics (Part Number FABPPOP100881)	N/A	Washers, Translucent, 0.125” Thickness, 0.257” ID, 0.500” OD
Fluoroelastomer (FKM) – Viton®	McMaster-Carr (Part Number 1284N164)	5002973292	O-Rings, White, 60A Hardness, 1/8” Factional Width, 1/2” ID, 3/4” OD
Perfluoroelastomer (FFKM) – Kalrez® 6375	McMaster-Carr (Part Number 1108T124)	D15573712	O-rings, Black, 75A Hardness, 1/16” Fractional Width, 1/2” ID, 5/8” OD
Nylon	McMaster-Carr (Part Number 92150A125)	840660-2	Washers, Translucent, 0.084-0.104” Thickness, 0.265” ID, 0.500” OD
Polychlorotrifluoroethylene (PCTFE)	Professional Plastics (Part Number FABPPOP100880)	N/A	Washers, Translucent, 0.125” Thickness, 0.257” ID, 0.500” OD
Polyether Ether Ketone (PEEK)	McMaster-Carr (Part Number 93785A910)	N/A	Washer, Beige, 0.056-0.071” Thickness, 0.281” ID, 0.500” OD
Polytetrafluoroethylene (PTFE)	McMaster-Carr (Part Number 9559K23)	190545	O-rings, White, 55D Hardness 3/32” Fractional Width, 3/8” ID, 9/16” OD
Polytetrafluoroethylene (PTFE) with Silica - Gylon® 3502	Garlock (Part Number 371341190)	N/A	Gaskets, Fawn, 0.125” Thickness, 0.844” ID, 1.875” OD
Silicone Rubber	Parker (Part Number S7442-40)	Serial Number 22-49	Hollow-Core O-ring, Rust Hardness (Shore) 45, 7.8” Diameter, Sectioned into smaller test samples

Material	Vendor	Lot Information	Details/Form/Nominal Size
Polyimide with Graphite Filler – Velspel® SP-21	Professional Plastics (Part Number FABPPOP100879	N/A	Washers, Grey/Black, 0.125" Thickness, 0.257" ID, 0.500" OD

7.2.7.3 Oxygen Compatibility- Autoignition Temperature and GOX Mechanical Impact Threshold Testing

AIT determination was completed for top replacement candidates and Vertrel MCA as a common tDCE-containing solvent currently in use. Testing was completed in accordance with a modified ASTM G72 [20] method by WSTF at 13.8 MPa (2000 psi) rather than the standard 10.3 MPa (1500 psi) to correlate with previous solvent evaluation studies and existing HFE-7100 AIT data [21]. A summary of AIT results is shown in Table 10; full results are provided in Appendix C.

Mechanical Impact Testing was performed for a few of the candidate solvents per ASTM G86 [22] to evaluate at what pressure threshold the candidates' solvents would ignite when impacted with a plumet at 97.6J of energy. This approach had been used during a previous solvent evaluation [1] in helping to identify least reactive recommended solvents in addition to AIT. Solvents were frozen prior to testing and test fixture chilled with LN2 prior to test to ensure material contact. A plummet catcher was used for all testing referenced below to reduce data variability.

Both AIT and ASTM G86 Pressure threshold evaluation methods allow for the ranking of solvents with respect to oxygen compatibility in order to help system designers to select "least reactive" materials for use in cleaning their components and systems. When non-preferred solvents must be used with performance in the "proceed with caution" category secondary flushes or other additional precautions (e.g., hydrocarbon lockup analysis, etc.) may be needed to ensure only trace amounts of these solvents remain inside oxygen systems post cleaning.

Table 10. Summary of AIT Results

Solvent	AIT, Minimum of 5 Replicates		AIT, Average of 5 Replicates		ASTM G86 Pressure Threshold (psi) at 97.6J
	°C	°F	°C	°F	
HFE-7100*	336	636	338	640	
BestSolv Sierra	243	470	249	480	
Ensolv Fluoro IC	398	749	401	754	
Opteon SF33	260	500	271	519	<500
Solstice PF*	180	356	182	360	7500
Amolea AS-300	151	304	158	317	<500
Vertrel MCA	138	281	152	305	
Opteon SF30	133	271	149	300	

** Data Provided from previous WSTF Testing, only 3 replicates were reported [21]. These solvents were not evaluated in this test series but are included here as important reference materials.*

In prior solvent evaluations [1] and [22], AIT acceptance criteria for use with oxygen systems was as follows:

- Category A: AIT > 204 °C (400 °F) – Acceptable for use in oxygen systems (designated in green text in Table 10)

- Category B: 121 °C (250 °F) ≤ AIT ≤ 204 °C (400 °F) – May be used with caution in oxygen systems (designated in orange text in Table 10)
- Category C: AIT < 121 °C (250 °F) – Not recommended for use in oxygen systems

Of solvents tested in this series, BestSolv Sierra, Ensolv Fluoro IC, and Opteon SF33 demonstrated AIT temperatures above 204 °C and are therefore considered the most favorable for oxygen system applications. Additional solvents tested such as Amolea AS-300, Vertrel MCA, and Opteon SF30 demonstrated AITs below 204 °C and are therefore of reduced oxygen compatibility. As previously mentioned, secondary flushing steps or other additional precautions may be needed to ensure only trace amounts of these solvents remain inside oxygen systems post cleaning based on AIT data.

7.3 Task 2: Identification and Initial Testing of Alternative Precision Cleaning Technologies

7.3.1 State-of-the-Art for Precision Cleaning Technologies

Precision cleaning involves the complete removal of unwanted contaminants or soils (residues and/or particulates) to achieve a desired level of cleanliness while preventing the introduction of new contaminants during the process [23]. Contaminants on critical components can lead to system failure, performance degradation, and safety hazards. For instance, high cleanliness levels are essential for oxygen systems, as even a small amount of contamination can increase the risk of fire or explosion [24]. Therefore, precision cleaning is crucial for safety and regulatory compliance, ensuring the reliability, quality, performance, and longevity of materials.

Several key factors influence precision cleaning processes including: (1) the required level of cleanliness, (2) the chemical and physical properties of the contamination, and (3) the material properties of the substrate. The cleanliness level is determined by the needs of the subsequent process and is typically set at the minimum threshold where no adverse effects occur [25]. For space hardware, this level is defined by program and system requirements, which specify allowable limits for particulates and non-volatile residues remaining on the surface after cleaning [26, 27].

Precision cleaning removes contamination by overcoming the adhesion forces of contaminants to the substrate surface through physical and/or chemical means [28]. Physical-assisted cleaning processes use mechanical agitation, fluid motion, and abrasives to clean surfaces. In contrast, chemical-assisted cleaning processes utilize solvents such as aqueous detergents, organic solvents, and chemical reactants to dissolve contaminants. To chemically remove contamination from the surface, the contaminants must be soluble in the solvents. The concept of like-dissolves-like is generally used in evaluating the solubility of contaminants [28]. Nonpolar (water-insoluble) contaminants dissolve in nonpolar solvents, whereas inorganic and polar compounds generally dissolve in polar solvents such as water [28]. Most precision cleaning processes employ both chemical and physical methods to remove a wide range of contamination.

Contamination can be classified into various categories, including microbial, particulate, inorganic, and organic compounds. Inorganic contaminants may include ionic compounds, salts, silicates, metals, metal oxides, and carbides [23]. Organic contaminants include hydrocarbon films, oil, greases, polymers, waxes, adhesives, resin additives, etc. [23, 27]. Particulates can consist of both organic and inorganic contaminants, such as metals, metal oxides, inorganic and chemical dusts, and polymers. Both organic, inorganic, and particulate contaminants, as well as

substrate surfaces, can be further classified as hydrophilic (water-soluble) or hydrophobic (water-insoluble) [23].

The physical and chemical properties of the contamination influence the dissolution efficiency of the cleaning medium, such as organic, aqueous, or fluorinated solvents. Organic solvents are typically used for dissolving hydrophobic and nonpolar contaminants, while aqueous-based solvents are generally used to dissolve ionic and polar contaminants. Fluorinated solvents are particularly effective at dissolving fluorinated and halogenated greases and oils. These cleaning media can be formulated to dissolve a broad range of contaminants by utilizing co-solvents and additives. Particulates that are insoluble in the cleaning medium are removed from surfaces through physical and mechanical methods.

Cleaning processes also involve wetting of the contaminants and the substrate [23]. The material properties, wettability, size, shape, and geometries of the substrate impact the efficacy of the cleaning method. The hydrophilic or hydrophobic properties of the substrate affect the wettability of the solvent, which can influence the amount of scrubbing energy needed to remove the contaminants [23]. Materials with complex geometries, internal surfaces, and holes require cleaning mediums that can penetrate deep crevices and blind holes. It is also important to select a cleaning medium compatible with the substrate to prevent negative chemical reactions that can damage or corrode the surface.

Contamination can be complex, comprised of a combination of organic, inorganic, soluble, insoluble, polar, nonpolar, and particulate matter. Various physical and/or chemical-assisted cleaning technologies are used to decontaminate surfaces. This section highlights that state-of-the-art for some of these technologies including sonic, solvent, aqueous, supercritical fluid, liquid CO_2, plasma, cryogenic aerosol, UV-ozone cleaning, and abrasive blasting. Cleaning mechanisms, merits, limitations, and process optimization of each cleaning technology are presented.

7.3.1.1 Sonic Cleaning

Sonic cleaning technology utilizes acoustic energy to remove contaminants and unwanted deposits from surfaces through acoustic streaming and cavitation [29]. It involves sonic irradiation (sonication) using acoustic waves at specific frequency ranges. Sonic cleaning primarily employs ultrasonic and megasonic frequencies. Ultrasonic frequencies generate random cavitation, while megasonic frequencies produce controlled cavitation [29]. Ultrasonic cleaning uses lower frequencies, below 200 kHz, whereas megasonic cleaning operates at frequencies above 800 kHz [29]. Industries generally use frequencies between 20 kHz and 50 kHz for cleaning [30]. Heavy-duty cleaning applications often use 20 kHz - 40 kHz to remove greasy contaminants from large parts and components [29]. Frequencies of 40 kHz -0 kHz are used to remove small particles from materials, while 100 kHz - 200 kHz are employed to gently clean delicate and sensitive surfaces such as silicon wafers, electronic components, and disk drive components [29, 23]. The 100 kHz - 200 kHz range is also used for cleaning with volatile solvents, as their low viscosity, high vapor pressure, and low surface tension generate mild cavitation during sonication [31]. Frequencies above 200 kHz are used for precise and ultrafine cleaning of semiconductor wafers, optics, and highly polished mirrors [29].

Cleaning Mechanism

Sonic cleaning technology involves immersing the contaminated material in a liquid medium, such as organic solvents, aqueous detergents, or supercritical fluids. Sonication enhances the cleaning rate and performance of these solvents. The cleaning medium is sonicated using the appropriate acoustic wave frequency, depending on the level of contamination on the surface and the sensitivity of the material to the sonic frequency. After sonication, the cleaned material is rinsed and dried.

Sonic cleaning technologies remove contaminants from surfaces via two main mechanisms: acoustic cavitation and acoustic streaming [29]. Although both mechanisms exist at every frequency, megasonic cleaning primarily relies on high-velocity acoustic streaming, while ultrasonic cleaning mainly removes impurities through acoustic cavitation [23]. Acoustic cavitation refers to the stimulated bubble activity in a liquid caused by the oscillation of acoustic waves in the medium [31]. It occurs when vapor bubbles form and collapse in a liquid due to pressure changes and mechanical forces [32]. These pressure changes result from a series of rarefactions and compressions that arise when an acoustic wave is transmitted through a liquid medium [32]. During compression, acoustic waves exert positive pressure on the liquid molecules, pushing them together [32]. Conversely, during rarefaction, the negative pressure exerted by the acoustic waves pulls the liquid molecules apart [32]. At rarefaction zones, cavitation bubbles form when the pressure drop reduces the boiling point of the liquid, and the acoustic wave generates sufficient negative pressure to overcome the surface area of the liquid [30, 32]. In compression zones, the positive pressure causes the cavitation bubbles to oscillate, condense into a liquid, and form vacuum bubbles [30, 32]. When these bubbles grow to an unstable size, compression leads to their violent collapse and implosion, generating shock waves and microscopic jets of liquid that impinge on the surface, dislodging contaminants [29, 30, 32]. The onset and intensity of cavitation bubbles are influenced by several factors, including ambient pressure, vapor pressure, viscosity and surface tension of the liquids, concentration of dissolved gases, and the duration and frequency of the acoustic energy [23].

Acoustic cavitation also produces dynamic pressure waves that transport displaced contaminants away from the surface via acoustic streaming [23]. Acoustic streaming is the time-independent flow of fluid driven by the loss of acoustic momentum and attenuation of acoustic waves in the fluid [33, 31]. It generates regions of recirculation, pressure gradients, and acoustic pressure which can lead to the transportation, deformation, and manipulation of bulk fluid [33]. Acoustic streaming in liquids provides sonochemical enhancement to contaminant removal [23, 29]. It is worth noting that the acoustic streaming becomes stronger with increasing acoustic frequency [23].

7.3.1.1.1 Merits, Limitations, and Process Optimization

Merits: Sonic cleaning is a versatile method which can be used to clean a wide variety of contaminants from various materials using a broad range of cleaning fluids including organic solvents, aqueous detergents, and supercritical fluids. Sonication provides mechanical energy boost to enhance the cleaning performance of these fluids. The mechanical agitation induced by acoustic energy enables faster dissolution of soluble contaminants and faster dislodgement of insoluble soils [30]. Sonication also allows for the cleaning of materials with complex geometries and irregular surfaces, as it generates cavitation implosions and releases energy that can reach deep crevices, internal parts, and blind holes [23].

Sonication has been employed to remove contaminants such as cutting oils, machining chips, greases, and polishing powders from various surfaces, including large metal components, electronics, and semiconductor wafers. It is particularly useful in aqueous cleaning, as it enhances the decontamination performance of aqueous detergents, providing a more environmentally friendly alternative to solvent cleaning. Sonication can also be applied during the rinsing step to ensure that residual solvents and detergents are removed from surfaces, preventing the rinsing agents from depositing new contaminants.

Limitations: There are some limitations associated with sonic cleaning. It is not suitable for materials sensitive to high-intensity vibrations, as it can cause erosion and deformation to delicate, fragile, and porous materials [23]. Surface erosion occurs due to the high-speed jets caused by cavitation implosion [29]. Even hard surfaces such as alumina, quartz, and silicon can be damaged by high-intensity ultrasonic fields and prolonged exposure to acoustic cavitation [23]. Repeated cleaning with acoustic wave can cause cavitation burns on glass surfaces [23]. It is important to optimize acoustic frequency, power, exposure time, and other parameters to mitigate surface erosion and damage.

Sonic cleaning is impractical for large-scale structures because it requires complete immersion of contaminated materials in the cleaning medium. The cleaning unit must accommodate the size of the materials and allow rotation or orientation for sonic energy to reach deep crevices [30]. Additionally, the unit must be designed to handle the corrosiveness or flammability of the liquid medium used during sonication. Sonication with flammable and volatile solvents requires an explosion-proof cleaning unit and facility. The cleaning medium must be compatible to the material composition of the cleaning unit. For example, the cleaning unit must be able to handle acidic or caustic cleaning agents without exhibiting corrosion. The cleaning medium must be carefully selected because it can affect the cleaning performance, operational parameters, and compatibility with the contaminated materials and the cleaning unit. Further discussion on the influence of the cleaning medium in the sonication process is provided in the following section.

Sonic cleaning can present safety hazards. Depending on the chemical, thermal, and physical properties of the cleaning medium, solvents can pose health and safety risks such as chemical exposure. The process can also produce high frequency noise which can be detrimental to personnel. It is important that personnel and anyone nearby are equipped with proper personal protective equipment (PPE) during operation. In addition, safety precautions and engineering controls must be established to ensure the process is safely performed.

Finally, as sonic systems tend to be static baths that must be drained and fluids reclaimed for reuse, there is additional processing time required, possibility of additional rinses of parts to ensure cleanliness, and difficulty in the ability to perform cleanliness verification without additional rinse steps.

Process Optimization: There are several factors that affect the sonic cleaning process. These include cavitation intensity, acoustic frequency and amplitude, the properties of the liquid medium, and temperature [23, 30]. Effective removal of contaminants is achieved by optimizing the combined effect of these factors.

As previously discussed, acoustic cavitation and acoustic streaming play crucial roles in the cleaning action of sonication. Cavitation affects the chemical and physical interactions between the liquid and the surface by inducing chemical reactions, acoustic streaming, and the formation of fluid jets and shock waves [31]. To improve the cleaning efficiency of sonication, it is

essential to optimize the cavitation intensity. This optimization depends on several factors, including acoustic frequency, power amplitude, and the properties of the cleaning liquid, such as temperature, viscosity, surface tension, density, vapor pressure, flow type (laminar or turbulent), and dissolved gases [23]. Cavitation intensity is directly related to ultrasonic power, which is proportional to the amplitude of the radiating wave [30, 23]. To exceed the cavitation threshold—the minimum acoustic energy needed to induce cavitation—sufficient ultrasonic power must be supplied to the transducer, the device that generates acoustic energy [23, 30]. The minimum power requirement for cavitation depends on the properties of the cleaning medium [23].

Cavitation intensity is also influenced by acoustic frequency. It increases with decreasing frequency, which affects the size of the cavitation bubbles [30, 32]. Higher frequencies generate smaller cavitation bubbles that produce less implosion energy [32, 30]. Reduced cavitation at higher frequencies can be mitigated by increasing the ultrasonic power [30]. Additionally, an increase in cavitation intensity leads to a reduction in the cavitation threshold [32]. It is worth noting that the cleaning performance of the acoustic frequency also depends on the type of contaminants. It was found that cleaning efficiency increases with decreasing frequency for the removal of particulates, while removal of thin film deposits of oils and fats is enhanced at higher frequencies [32].

Further, cavitation intensity is influenced by the chemical and thermophysical properties of the cleaning medium. Physical properties such as viscosity, density, vapor pressure, surface tension, and dissolved gases can affect cavitation intensity [23]. These properties are temperature-dependent, so optimizing cavitation intensity involves maximizing the temperature of the fluid during the process. Fluids with higher surface tension require more energy to produce cavitation bubbles [23]. Hence, some cleaning mediums are formulated for ultrasonic cleaning by adding surface-active agents that lower the surface tension [30, 23]. Vapor pressure of the fluids also affects the production of cavitation bubbles. It is more difficult to generate cavitation bubbles in liquids with low vapor pressure [23]. Increasing the fluid temperature can improve vapor pressure, which reduces surface tension and lowers the cavitation threshold for generating microbubbles [23]. Additionally, viscosity affects cavitation intensity, as viscous liquids are slower to produce cavitation bubbles [30]. Dissolved gases can also influence cavitation by preventing violent implosions when released during the bubble growth stage of cavitation [30]. Many ultrasonic units also have a de-gassing feature to remove dissolved gases from the cleaning medium prior to use.

The selection of the cleaning medium significantly impacts the performance of sonication. The cleaning medium influences cavitation intensity, cleaning rate, and the mechanism of contaminant removal. It is crucial to select a cleaning medium based on material compatibility, its cavitation efficiency at various frequencies, and its effectiveness in dissolving contaminants [23]. Some chemicals do not cavitate well, so it is necessary to choose chemicals compatible with acoustic energies to generate cavitation. The cleaning medium must also be compatible with the contaminated materials and the cleaning unit [23]. Additionally, the cleaning medium should be capable of solubilizing contaminants to effectively remove soils from the surface [30].

7.3.1.2 Solvent Cleaning (Vapor Degreasing)

Solvent cleaning employs chemical solutions to dissolve unwanted deposits such as oil, grease, residue, and other contaminants from surfaces. This process has been used since the late 19th

century and is widely used in various industries such as aircraft, automotive, and electronics. There are two types of solvent cleaning processes: vapor degreasing, where the solvent is vaporized, and cold cleaning, where the solvent is not vaporized [34]. Cold cleaning techniques include spraying, immersion, mechanical or ultrasonic scrubbing, flushing, etc. The term "vapor degreasing" is somewhat misleading, as it is the condensed solvent vapor (liquid) that solubilizes the contaminants and acts as the degreasing agent [34]. The remainder of this section will focus specifically on vapor degreasing.

7.3.1.2.1 Cleaning Mechanism

Vapor degreasing cleans surfaces by using hot solvent vapors to remove contaminants. These vapors condense on the surface, creating a liquid flow that dissolves and washes away the soil as the condensed solvent drains off by gravity [35]. When heavy soil cannot be removed by vapor degreasing alone, an initial solvent scrub may be needed to remove the soil, followed by vapor degreasing to eliminate any remaining oils and greases [36]. Effective vapor degreasing requires the right type of solvent and appropriate degreasing equipment [36]. Solvents are selected based on the contaminants to be removed, following the principle "like dissolves like." A polar solvent is selected for polar contaminants, and a nonpolar solvent is chosen for nonpolar contaminants.

Typical schematic diagrams of a vapor degreasing system can be found in literature [37]. They are constructed with one large tank divided at the bottom into two sections: a boil sump and a rinse sump. Both sumps contain the solvent used for cleaning. The vapor degreaser is filled from the rinse sump, which spills over into the boil sump, ensuring the rinse sump is ideally the less contaminated sump. Two sets of chilling/condensing coils keep the vapor contained within the tank; or condense it. A water separator and condensate return loop direct the condensed vapor back to the rinse sump. The rinse sump is equipped with a pump and filter for circulation. The boil sump contains heaters and often ultrasonic transducers, while the rinse sump also includes ultrasonic transducers and spray nozzles.

The typical vapor degreasing process is as follows: Contaminated parts are placed in a metal wire basket and lowered into the vapor zone for a period of time. This step begins to loosen the contaminants while also raising the temperature of the parts to near the temperature of the boil sump. The parts are then lowered into the boil sump, where ultrasonic transducers are activated to facilitate the removal of contaminants. Some systems may operate these ultrasonics in a multi-step series at different frequencies to target various layers of soil. Additionally, some systems include a high-pressure sprayer in the sump to aid in cleaning. The basket is pulled back up into the vapor layer, moved over to the rinse sump, and lowered into the rinse sump. After rinsing, it is pulled up into the vapor zone again to drain and dry. Finally, the basket is raised above the primary condensing coils to fully dry. When dry, the vapor degreaser is opened from the top and the parts basket is removed [38].

Vapor Degreasing Systems: While the basic operation of vapor degreasers is very similar, the design can vary depending on size, capacity, or throughput volume. One of the most common configurations is the open-top tank, which may include design modifications to affect the freeboard height or the atmosphere/vapor interface to preserve the vapor blanket.

For higher throughput and automation, some systems incorporate conveyors, such as in-line cleaners, monorail degreasers, or cross-rod degreasers. In-line and monorail degreasers typically feature a sloped tunnel design, where parts are transported on a hanging conveyor from outside the machine, through the vapor zone, and then out of the system. The monorail degreaser

includes an additional step in which parts are immersed in the boil sump before returning to the vapor blanket. The cross-rod degreaser, on the other hand, has a footprint similar to that of the open-top design.

The open-top vapor degreasing system operates with a heater at the bottom to boil the solvent and a cooling surface at the top to condense the vapors [39]. The operation is simple yet effective: vapors from the boiling solvent condense on the cool parts, dissolving and flushing away oils, greases, and other contaminants [39]. Once the part reaches vapor temperature, condensation ceases, and the clean, dry part is removed [39]. As the solvent vapors rise, they displace air in the tank and are contained by condensing coils and a water jacket located below the freeboard area. When vapors reach the cool zone, they condense on the coils. Although efficient and cost-effective, this process allows a high percentage of solvents to escape into the atmosphere [39].

In contrast, vacuum degreasers are fully enclosed systems. Parts are placed in a basket and loaded into a dry chamber. Once sealed, the chamber is activated and filled with solvent vapor for cleaning. Some systems also incorporate hot solvent rinses, sprays, or sonication to remove contaminants. The main advantage of a vacuum degreaser is that it fully contains the solvent, preventing losses and reducing personnel exposure. However, it is more complex and requires additional maintenance compared to a traditional open-top degreaser.

Common Solvents Used in Vapor Degreasing: Effective vapor degreasing requires the right type of solvents which must possess several key properties such as high solvency for the contaminant(s) of interest, nonflammability, non-explosiveness, and nonreactivity under operating conditions [36]. The solvents should have a high vapor density and low diffusion rate to minimize loss, a low heat of vaporization and specific heat to optimize condensation and reduce heat consumption and be chemically stable and noncorrosive [36]. Additionally, they must be safe to operate with, have a suitable boiling point for easy distillation and condensation, and comply with air pollution control regulations [36]. Solvents with low boiling points evaporate quickly, enabling faster drying, while those with higher boiling points may offer deeper cleaning but require longer drying times [40].

Historically, vapor degreasing relied on solvents like trichlorotrifluoroethane (Freon 113) and 1,1,1-trichloroethane (TCA). While effective, these solvents posed significant health, safety, and environmental risks [36]. Their use was phased out following the Montreal Protocol due to their ozone-depleting potential. In response, PFCs were introduced as replacements, though they offered limited cleaning performance on their own. The next generation of replacement solvents, HFCs and HFEs, provided better cleaning performance when combined with a surfactant (such as Petroferm Solvating Agent 18, 19, 24, or 70) or by creating azeotropic solvent systems with compounds like methanol or tDCE [38].

Solvents that have been commonly used include trichloroethylene, perchloroethylene, modified alcohols, hydrocarbon solvents, and halogen-free solvents. Chlorinated solvents like trichloroethylene, perchloroethylene, and methylene chloride were ideal for vapor degreasing due to their high solvency for organic materials and compatibility with various materials such as metals, glass, and some plastics, or elastomers [41]. Additionally, they were nonflammable in air under most conditions and had low energy requirements due to their low latent heat of vaporization [41]. However, most of these solvents are no longer utilized due to regulatory limitations and health considerations. HFE solvents were widely adopted for precision cleaning

applications due to their nonflammability, low GWP, zero ODP, and sufficient cleaning efficiency. These HFEs are volatile organic compound (VOC)-exempt and compatible with a variety of materials. However, HFEs face the possibility of becoming obsolete due to regulatory pressures and manufacturing phase-outs [42] for PFAS materials. A comprehensive list of acceptable chemical solvents for precision cleaning applications was published by the EPA [43]. This document provides details on the ODP, GWP, and flammability of the solvents, along with guidelines on exposure limits and safety requirements [43]. It also includes information on aqueous and semi-aqueous cleaners, supercritical fluids, plasma, and UV-ozone cleaning methods.

7.3.1.2.2 Merits, Limitations, and Process Optimizations

Merits: Vapor degreasing is well-known for its benefits; it combines cleaning, rinsing, and drying using a single chemistry [39]. Parts are washed at every stage of the cleaning process with soil-free distilled solvent [11]. Vapor degreasers work faster than aqueous cleaners, effectively dissolving heavy greases and oils. The solvents evaporate quickly without leaving residue, making them safer for electronics due to higher compatibility, less corrosion, and minimal residue [44]. Solvent vapor degreasing also minimizes energy and solvent consumption. The ability to distill and recycle solvents for continued use reduces waste disposal and solvent consumption. Unlike aqueous detergents, solvent vapor degreasers do not require precise chemical combinations. Additionally, the vapor degreasing process can be automated in some machines, ensuring consistent and reproducible cleaning performance.

Limitations: One of the main drawbacks of vapor degreasers is solvent loss, which can occur through emissions, drag-out, and leaks. To minimize this, the degreaser must be properly sized not only for the dimensions of the parts and baskets but also for the mass of the parts and the cleaning frequency per hour. If the heat input is inadequate for the workload, or if the heating and cooling systems are not properly balanced, the vapor blanket can become unstable. This disruption leads to excessive solvent consumption and increased emissions.

If the heat input is insufficient or a heavy workload is introduced, the vapor blanket in a degreaser can collapse, allowing ambient air to enter the system. Depending on the temperature and humidity of this incoming air, solvent may diffuse into it. When the vapor blanket is re-established, this solvent-laden air is expelled, resulting in significant emission losses. Additionally, improper cooling of the condensers can introduce water into the system, disrupt the vapor height or depth, and lead to an unstable vapor layer, all of which further compromise efficiency and increase solvent loss [45].

Some solvent losses in vapor degreasers are due to their design, particularly factors like freeboard height (the distance from the centerline of the cooling coils to the top of the unit), the vapor/air interface, and the type of cover used. Solvent diffusion losses are inversely related to both the freeboard height and the size of the vapor/air interface—meaning taller freeboards and smaller interfaces reduce losses. Covers that move vertically tend to disrupt the vapor blanket more than those that slide or roll horizontally. Lifting a cover upward draws vapor out of the chamber, while lowering it can push the vapor blanket out, both actions contributing to unnecessary solvent consumption [45].

Additionally, as with other technologies, the ability to perform cleanliness verification without the use of additional rise steps or modified systems can be difficult to achieve with vapor degreasing, and there can be limitations of the technology use with large/complex parts (e.g.,

large-diameter, long flex hoses where only the internal surface requires cleaning, complex parts with intricate dead volumes and small diameter flow paths, etc.).

Process Optimizations: Optimizing vapor degreasing requires several key steps to ensure both efficiency and effectiveness. These steps include improving the design of the vapor degreasing system and optimizing the solvent recycling process.

Solvent cleaning systems are typically categorized as open or closed. Open systems such as vapor degreasing, ultrasonic cleaning, solvent immersion, and solvent spray system are widely used but suffer from high solvent loss, environmental emissions, and costly waste management [46]. Traditional open-top degreasers experience solvent loss due to drafts, parts loading, and solvents carried by cleaned parts [41]. Up to 70% of the solvent can be lost annually [41]. Implementing procedures to minimize this loss is essential to keep vapor exposure below OSHA regulations and meet EPA requirements [41]. Closed systems are designed to minimize emissions; however, solvent loss still occurs as vapor escapes during part removal and residual solvent adheres to surfaces or remains trapped within porous materials [46]. Solvent recovery is often inefficient and expensive.

Conventional solvent cleaning systems such as open and closed systems face persistent challenges related to hazardous emissions, solvent recovery, and operational limitations. These systems typically operate at specific temperatures and pressures, often dictated by the boiling point of the solvent at atmospheric pressure [46]. They may not fully remove solvent residues before exposing cleaned parts to the atmosphere, leading to further emissions. Additionally, they require large volumes of solvent to fill cleaning tanks and consume significant energy to circulate and heat the solvent. Solvent vapor systems, in particular, rely on solvents with vapor densities greater than air, necessitating the use of refrigeration coils and restrictive tank designs to contain the vapors effectively [46].

Vacuum Degreasing: Very similar to vapor degreasing, vacuum degreasers offer an alternative approach to traditional conventional degreasing systems by addressing many of their inherent limitations through advanced design and controlled operation. In a typical vacuum degreasing process, parts are loaded into a sealed chamber, which is then evacuated to pressures below 1 torr to remove air. Once under vacuum, the pressure to the vapor supply tank is equalized, and solvent vapor fills the degreasing chamber. Depending on the operation, hot solvent may be pumped from the vapor supply tank for soaking or spraying purposes. Cooled solvent may be pumped from the storage tank to the degreasing chamber and eventually to the vapor supply tank. The system is designed to recover solvent vapors at the conclusion of the cleaning cycle, directing them back to either the vapor supply or storage tank. This closed-loop configuration minimizes solvent emissions, enhances operator safety, and enables the safe use of flammable solvents. To further improve cleaning performance, vacuum degreasers may incorporate ultrasonic agitation and mechanical features such as rotating or tilting baskets, which enhance both cleaning effectiveness and drying efficiency [47].

Vacuum degreasing also presents certain limitations. While it effectively removes contaminants by vaporizing them under reduced pressure and elevated temperatures, many contaminants have low vapor pressures, necessitating extremely high vacuums and significant thermal input for effective removal [46]. This results in high energy consumption and operational costs. Furthermore, NVRs, either present in the original contamination or formed through thermal degradation, may remain on component surfaces, reducing cleaning effectiveness [46]. Although

vacuum degreasing eliminates solvent emissions, it may still release contaminants into the environment and is often constrained by stringent pollution control requirements [46]. These factors collectively limit its broader industrial applicability.

Vacuum Cyclic Nucleation: An alternative approach, Vacuum Cyclic Nucleation (VCN), is an advanced closed-loop cleaning technology developed for the effective internal cleaning of components with complex geometries and confined voids [46]. The VCN process was invented by Vacuum Processing Systems [46]. VCN offers superior performance in both aqueous and solvent-based systems, while significantly reducing solvent consumption and environmental emissions. The process begins by placing the part to be cleaned in a sealed chamber, which is then evacuated to remove air and non-condensable gases [46]. This pre-evacuation step prevents solvent-air mixing, eliminating the need for complex vapor recovery systems. Solvent is introduced into the chamber in liquid, vapor, or combined phases, driven by the pressure differential between the solvent reservoir and the chamber, without requiring mechanical pumps [46]. The chamber's temperature and pressure can be precisely controlled to optimize solvent penetration and vapor density [46].

VCN operates through rapid vacuum-pressure cycling to achieve effective internal cleaning of complex components. The process begins with an initial vacuum cycle that removes air from internal cavities, followed by a pressure cycle that forces cleaning fluid into these voids [48]. Subsequent vacuum phases generate vapor bubbles within the internal structures, displacing fluid along with dissolved contaminants, particulates, surfactant micelles, and reaction by-products [48]. Each pressure cycle then introduces fresh cleaning fluid, replenishing treatment chemicals and enhancing contaminant removal. This cycle is repeated until complete cleaning is achieved, ensuring thorough penetration and flushing of internal features [48].

VCN supports both aqueous and solvent-based systems and accommodates a wide range of solvents, including halogenated hydrocarbons, alcohols, ketones, and aromatics, regardless of vapor density [46]. It also accommodates temperature-sensitive materials through integrated thermal control. Additionally, the initial vacuum step aids in pre-cleaning by removing volatile contaminants before solvent introduction. Overall, VCN provides a highly efficient, environmentally responsible, and cost-effective alternative to conventional open-loop cleaning methods, making it particularly valuable in industries requiring high-precision cleanliness, such as aerospace, electronics, and additive manufacturing. Several limitations exist with the technology. At this time, VCN is limited in the ability to validate cleanliness directly, especially when using an aqueous-based cleaning method, possibly requiring additional rinse steps or additional development of the system. Additionally, there are limitations in the ability to filter used detergent/solvent solutions during and after the cleaning is finished for ease in recycling and reuse of the fluids.

Solvent Recycling: The efficiency and environmental sustainability of vapor degreasing operations can be significantly enhanced through the optimization of solvent recycling processes. Effective solvent recovery not only reduces waste generation but also minimizes solvent consumption, contributing to cost savings and regulatory compliance. Maintaining the efficiency of this process requires regular monitoring to ensure consistent performance and to detect any deviations that may compromise solvent quality or system operation.

In vapor degreasers equipped with dual-sump configurations, solvent recycling is typically achieved through a controlled distillation process. Initially, solvent is drawn from the spray

reservoir or condensate sump. The boil sump is then distilled down to a level approximately one inch above the heating elements, during which the solvent is vaporized. The vaporized solvent is subsequently condensed and collected in the condensate sump, while the remaining mixture of contaminants and residual solvent in the boil sump is removed for disposal or further reclamation. When azeotropic solvents are used, the reclaimed solvent must be analyzed for stabilizer or inhibitor concentrations and adjusted in accordance with the manufacturer's recommendations to maintain solvent integrity and system safety [45].

Advanced solvent recovery systems incorporate auxiliary stills that operate continuously to further enhance the efficiency and effectiveness of the recycling process. These systems may include an oil/water separator, which separates and directs oil for recovery while routing waste and water to appropriate disposal streams; a solvent/water separator, which collects input from all degreaser water separators and directs water to disposal and solvent to recovery or further distillation; and the still itself, which utilizes steam from the degreaser to facilitate distillation and sends the output to the oil/water separator and the solvent/water recovery tank [45]. These integrated systems support continuous operation, reduce downtime, and improve overall solvent utilization, making them a valuable addition to modern vapor degreasing operations.

7.3.1.3 Aqueous Cleaning

Aqueous cleaning utilizes water-based cleaning solutions or detergents containing minimal or no VOCs to remove surface contaminants [49]. To enhance the cleaning efficacy of water, aqueous detergents are typically formulated with chemical additives such as surfactants and builders, although surfactant-free formulations are also available [50]. Surfactants function as wetting agents, enabling the cleaning solution to penetrate fine crevices and adhere to soils. They also facilitate the emulsification of hydrophobic, water-insoluble oils and the dispersion of particulate matter [50]. Builders, on the other hand, act by sequestering dissolved metal ions, thereby preventing these ions from interfering with the cleaning process and maintaining the stability and effectiveness of the detergent system [50]. The aqueous cleaning process combines thermal energy, mechanical agitation, and chemical action to dislodge and remove contaminants from surfaces [49]. Detergents lift contaminants through chemical interaction, while heat enhances the solubility of soils and improves the compatibility of the detergent with the substrate [51] Mechanical agitation further aids in the physical removal of contaminants.

7.3.1.3.1 Cleaning Systems and Mechanisms:

Aqueous Detergents: While water serves as the primary solvent in aqueous cleaning, it is inherently limited in its ability to dissolve non-polar substances such as fatty and mineral oils. Cleaning with water alone, whether heated or applied under high pressure, is often insufficient, as it requires large volumes, frequent replenishment, and may not achieve complete removal of organic residues. To overcome these limitations, surfactants are incorporated into aqueous cleaning formulations due to their ability to effectively target and remove non-polar contaminants.

Surfactants, also referred to as tensioactive agents or tensides, are amphiphilic organic compounds composed of both hydrophilic and hydrophobic parts [52]. This dual affinity enables them to adsorb at interfaces, such as between water and metal or metal oxide surfaces [52]. Surfactants are generally classified into four categories based on the charge of their hydrophilic head group: anionic (negatively charged), cationic (positively charged), nonionic (no net charge), and zwitterionic (contain both positive and negative charges) [52]. A subset of zwitterionic

surfactants, known as amphoteric surfactants, exhibit pH-dependent charge behavior [52]. Nonionic surfactants include compounds such as poloxamers, ethoxylates, alkyl-phenyl ethoxylates, sorbitan esters, alkyl polyglycosides (APGs), biosurfactants, and fatty alcohols, which are valued for their biodegradability and can be modified with ethylene oxide units to produce low-foam detergents [25]. Anionic surfactants, such as sodium dodecyl sulfate, are known for their strong foaming and cleansing properties. Other examples include alkylbenzene sulfonates, sulfosuccinates, alkyl phosphates, and fatty acid salts (soaps), each offering specific advantages such as solubility in water or oil-based systems [25]. Cationic surfactants, commonly referred to as quaternary ammonium compounds, include trimethylammonium alkyl halides (e.g., cetyltrimethylammonium bromide). While compounds like benzalkonium chloride and pyridinium chlorides are not strong surfactants, they are widely used for their antimicrobial properties. Modified quaternary pyridinium amines are capable of dispersing inorganic materials in oils or organic substances in water, although they tend to be unstable under basic conditions [25].

Surfactants are essential in both aqueous and semi-aqueous cleaning processes. They enhance cleaning by wetting contaminated surfaces and facilitating soil removal through mechanisms such as dispersion, emulsification, and sequestration [25]. For water-based systems, several key parameters must be optimized, including pH, surface tension, surfactant concentration, rinsability, filtration capability, and operating temperature [25]. These factors are carefully engineered by chemical manufacturers to ensure performance and material safety [25].

Cleaning Mechanisms: Aqueous cleaning employs a variety of chemical and mechanical processes to effectively remove contaminants. These processes include solubilization, which enhances the ability of a substance to dissolve contaminants; wetting, which lowers surface tensions to allow cleaners to penetrate and lift soils from the substrate; and emulsification, which prevents oil droplets from recombining [50]. Additionally, deflocculation disperses soil particles, sequestration prevents formation of insoluble by-products, saponification converts fats into water-soluble soaps, and hydrolysis breaks down larger molecules into smaller, more soluble residues [50]. Together, these mechanisms ensure thorough cleaning and effective contaminant removal.

There are various approaches to aqueous cleaning. Hot water cleaning removes gross organic and particulate contamination using a spray system or cleaning vat at low to moderate heat. Water-soluble contaminants are removed with a hot or cold rinse of detergent-free water before the cleaning agents have time to precipitate. Parts can then be dried with air, which may be heated to shorten drying time. Steam cleaning uses pressure and heat to decrease the viscosity of contaminants. Detergents can emulsify organics, allowing for removal by the condensed steam. Caustic and detergent cleaning combines water with detergents and surfactants to remove organic contamination such as hydrocarbon oils, greases, and waxes. Inhibitors, pH buffers, saponifiers, emulsifiers, antifoaming agents, and wetting agents can be added to detergents to enhance cleaning effects. These solutions can be used in immersion tanks or pumped or jetted through components. The solution can be reused until it becomes ineffective, as determined by pH or contaminant concentration analysis [53].

Cleaning Systems: Aqueous cleaning systems come in various configurations tailored to specific applications and part requirements. Top-loading parts washers use spray cleaning for smaller components, offering a compact and efficient solution. Rotary drum washers feature a rotating screw mechanism that moves parts through a combination of jet spray and immersion cleaning,

ideal for high-volume, continuous processing. Conveyor belt washers transport parts along an enclosed belt system, providing thorough spray cleaning and rinsing as they move through different zones. For larger or grouped components, monorail washers carry parts through multiple enclosed stages, which can be customized for spray, immersion, or ultrasonic cleaning, depending on the cleaning needs [54]. Aqueous cleaning systems range in size from compact benchtop units to large, room-scale, or lab-scale installations, depending on factors such as part size, cleaning application, number of stages, and desired level of automation. Many commercial equipment manufacturers offer customizable features to tailor scalability and throughput to specific operational needs [54, 55]. Power requirements for aqueous cleaning equipment vary based on the application, system features, and overall size of both the main and auxiliary components. For example, a small heated ultrasonic bath may require around 1 kW of power, while a large-scale system—equipped with heaters, pumps, ultrasonics, and support equipment capable of handling up to 1,000 gallons of water—can demand over 350 kW [55].

7.3.1.3.2 Merits, Limitations, and Process Optimization:

Merits: Aqueous cleaning systems offer several advantages, particularly in terms of environmental and economic performance. Compared to chlorinated, fluorinated, and brominated solvents, aqueous cleaners present fewer environmental hazards and are often more cost-effective due to lower disposal and regulatory compliance costs [44]. While aqueous cleaning is often described as gentle, this characterization depends heavily on the formulation; for instance, caustic and acidic solutions can still pose significant risks to living organisms and materials if not properly managed [44].

Modern aqueous cleaning systems may incorporate closed-loop designs that enhance sustainability and operational efficiency. These systems are capable of processing multiple batches of parts while capturing sludge, sediment, and oil for recycling or remediation. The number of cleaning cycles achievable before solution replacement depends on several factors, including detergent formulation, soil load, and the efficiency of the recapture system. For example, caustic solutions can be reused until they become ineffective, as determined by pH monitoring or contaminant concentration analysis [56].

From a cost perspective, aqueous cleaners are generally economical due to their concentrated nature, typically requiring only 1% – 5% cleaner to water. These solutions also exhibit long bath life without the need for frequent recycling. However, strong acid cleaners can increase operational costs due to their corrosive properties, which may damage tanks, pumps, and other system components, as well as the parts being cleaned. Additionally, metal soil loading in acidic baths often necessitates frequent decanting and disposal, further elevating maintenance and material costs [50]. In contrast, alkaline cleaners are typically more cost-effective and less corrosive, resulting in reduced maintenance requirements. When selecting detergent formulations, it is important to evaluate the presence of non-functional fillers, such as sodium chloride or sodium sulfate in powders, or excess water in liquid formulations, which add volume and weight without contributing to cleaning performance [24]. Identifying and avoiding such fillers can further improve the cost-efficiency and effectiveness of aqueous cleaning operations.

Limitations: While aqueous cleaning systems are adopted for their environmental benefits, they present several operational and safety limitations that must be carefully evaluated during system selection and implementation. One of the primary drawbacks is high water consumption, as water constitutes the bulk of the cleaning solution. This is accompanied by significant energy

demands, primarily due to the need for continuous heating and circulation of large volumes of water. These factors contribute to elevated operational costs, driven by the integration of advanced technologies such as heaters, pumps, ultrasonic transducers, and monitoring systems required for efficient and controlled operation [44].

The complexity of these systems also necessitates routine maintenance to ensure consistent performance and to prevent equipment degradation or failure. Additionally, the presence of chemical agents in aqueous formulations introduces occupational health risks. Potential hazards include chemical burns, skin irritation from prolonged exposure, and respiratory issues resulting from the inhalation of mists or vapors, which may irritate the respiratory tract [44]. Another concern is the risk of recontamination during the cleaning process. When removing organic and ionic contaminants, the quality of rinse water and the control of rinsing parameters are essential. Inadequate rinsing or poor water quality can leave behind detergent residues or ionic salts, which may act as new sources of contamination [25]. Additionally, drying challenges can impact surface quality. If drying is delayed or inefficient, deionized water may react with freshly cleaned active surfaces, particularly soft metals, at elevated temperatures, resulting in staining or surface marks [25]. Aqueous cleaning systems may also have difficulties in the ability to validate the cleanliness level from aliquots of the aqueous cleaning solutions if detergents are still present; if final rinses are with filtered, pure water, this may or may not be a limiting factor for the technology.

Process Optimization: The effectiveness of aqueous cleaning systems is influenced by a range of operational parameters. Key factors include the nature of the contaminant and substrate, the selected cleaning method, water temperature, solution pH, ultrasonic frequency (if applicable), tank or reservoir size, rinse quality, and the temperature and efficiency of the drying process. Additionally, the chemical composition of both the contaminant and the substrate plays a critical role in determining appropriate cleaning chemistry and process parameters [54].

While some systems incorporate automation and water recycling technologies to reduce consumption, water remains a significant resource input. To improve energy efficiency and operational costs, several design strategies can be implemented. These include the use of thermal insulation to minimize heat loss, internal reservoir covers to reduce evaporation, appropriately sized pumps to optimize fluid dynamics, and steam exhaust dampers [55]. Industrial aqueous cleaning systems also include safety and environmental features to protect both operators and the surrounding environment. These may consist of secondary containment to manage spills, protective covers to prevent hot water splashes, and electrical safety disconnects to ensure operator safety. Additionally, noise reduction can be achieved through acoustic insulation and optimized mechanical design, which is particularly important in high-throughput environments [55].

Selecting an appropriate detergent is essential for effective cleaning and material compatibility. It is essential to choose one that is compatible with the cleaning method and suitable for the specific soils and component materials involved. The detergent must be compatible with the cleaning method, noncorrosive to the component, and should have excellent free-rinsing qualities [50]. The type of soil present on the component is another critical determinant in detergent selection. Whether the soil is heavy or light, organic or inorganic, oil or particulate matter, it significantly influences the cleaning strategy [50]. Heavy soils typically require aggressive detergents with high concentrations of active ingredients. Cleaners that can disperse bulk

quantities of soil without needing to react chemically with each molecule are ideal for heavy soils [50].

Vacuum Cyclic Nucleation for Aqueous Cleaning: As discussed above, an alternative to conventional aqueous cleaning methods is the implementation of a VCN system [46, 48]. This advanced closed-loop cleaning technology addresses several limitations associated with traditional aqueous cleaning, particularly in applications involving components with complex geometries, blind holes, and deep cavities. As previously discussed, VCN is compatible with both aqueous and solvent-based cleaning media, offering versatility across a wide range of materials and contamination types. The system incorporates precise thermal control, enabling safe and effective cleaning of temperature-sensitive components. VCN provides a cost-effective and environmentally responsible alternative to conventional aqueous cleaning processes [46, 48].

7.3.1.4 Supercritical Fluid Cleaning

Supercritical fluids (SCF) are substances that are compressed above their critical temperature (T_c) and critical pressure (P_c) [57]. At these conditions, the distinction between gas phase and liquid phase disappears, forming a single-phase mixture with gas-like and liquid-like properties that are attractive for precision cleaning applications [58]. The supercritical fluid phase combines the characteristics of gases and liquids which enhance the viscosity, density, diffusivity, and solvating power of the fluid. SCF has low viscosity and very low surface tension which improves the diffusivity and wetting properties of the solvent. These properties improve its mass transport characteristics enabling faster and more efficient precision cleaning of materials with rough surfaces, intricate parts, and complex structures [58, 59]. In addition, the liquid-like density of the supercritical phase enhances the solvating power of the fluid to dissolve contaminants [58]. The solvating power of SCF is a function of density which can be modified by varying the pressure and temperature to optimize cleaning efficiency [28]. The tunability of the solvation properties are desirable characteristics of SCF for precision cleaning processes.

Supercritical phase can be attained by solvents such as methanol, acetone, water, argon, propane, methane, etc. [58]. The most studied, and widely preferred, SCF is supercritical carbon dioxide ($SCCO_2$) because of its favorable thermal, physical, chemical, environmental, critical, and solvent properties. $SCCO_2$ has several advantages over the other SCFs. In particular, the supercritical phase of CO_2 is readily attainable with a moderate critical pressure of 73 atm (1070 psi) and near ambient critical temperature of 31 °C (88 °F) [57, 59]. For comparison, water has critical pressure of 218 atm and critical temperature of 373.98 °C [58]. $SCCO_2$ is used in several applications including power generation, energy conversion, extraction processes, dyeing, chromatographic processes, and precision cleaning [60, 61, 62].

7.3.1.4.1 Cleaning System

A schematic diagram of a typical $SCCO_2$ cleaning system is shown in Figure 21 [58, 63, 59]. The system includes a cleaning chamber and CO_2 distillation chamber. The materials to be cleaned are placed inside the cleaning chamber which consists of heavy-duty and robust high-pressure vessels that can withstand the critical parameters needed to achieve the supercritical phase. Liquid CO_2 is pumped into the chamber which is then heated and pressurized above the critical points. Co-solvents can be added as needed and often injected into the flowing stream of $SCCO_2$ [58]. The cleaning chamber can be equipped with agitation systems that enable turbulent or convective flow which improves the removal rate of contaminants from the surface [28]. A dynamic or flowing process decreases the boundary layer which leads to faster dissolution of

contaminants [28]. In addition, the cleaning chamber can be integrated with an ultrasonic system to help facilitate removal of insoluble particulates that are strongly adherent to the surface of a substrate. After the cleaning process, the contaminated LCO_2 is transferred to the distillation chamber where phase separation and CO_2 recycling takes place making $SCCO_2$ cleaning a closed-loop process. In the distillation chamber, LCO_2 is converted into gaseous CO_2 by reducing the pressure of the chamber. This allows phase separation between the contaminants and the CO_2 gas. Gaseous CO_2 is evacuated and goes through a condenser where it is converted to LCO_2, ready to be used for the next cleaning cycle. The contaminants are then transferred to the waste stream. Depending on the boiling point and other properties, co-solvents may be recovered or sent to the waste stream.

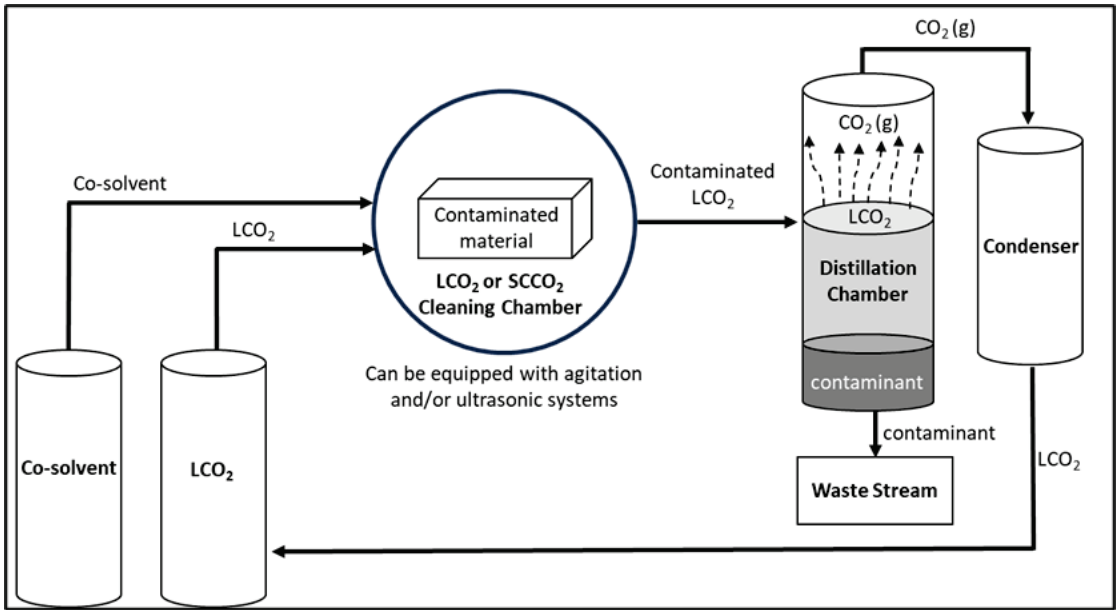


Figure 21. A schematic diagram of LCO_2 or $SCCO_2$ cleaning system [58, 59, 63].

7.3.1.4.2 Merits, Limitations, and Process Optimization

Merits: The physical properties of $SCCO_2$ offer several advantages for precision cleaning applications. Combining the properties of the gas and liquid phase, supercritical CO_2 has very low surface tension, 0.05mN m^{-1}, which gives the fluid its excellent wetting and mass transport properties to enable cleaning of materials with complex geometries, small pores, and deep crevices [58]. $SCCO_2$ has low viscosity, 0.0137mPa•s, which enables the fluid to be operated at turbulent flow which decreases the boundary layer resulting to faster dissolution rate of contaminants [58, 28]. Turbulent flow also provides shear force for mechanical removal of surface contaminants.

The solvent property of $SCCO_2$ enables dissolution of contaminants from the substrate. The solvating power of $SCCO_2$ is due to its liquid-like density that is tunable by controlling the temperature and pressure of the fluid. The ability to tune density allows for selective removal of contaminants. In addition, the nonpolar characteristic of CO_2 offers an excellent solubility for hydrocarbons, greases, cutting oils, machining fluids, lipophilic solvents, fluorocarbons, low-volatility solvents, low-molecular weight and other nonpolar organic compounds [64, 65, 59, 66, 67, 68]. A group at KSC evaluated the cleaning efficiency of $SCCO_2$ for removal of Krytox 140AC, a fluorinated grease, from aluminum coupons [69], as well as mixed contaminants

(hydrocarbon oils, fluorinated greases, etc.) on metal fittings of varied complexity. Their results showed that pressure, temperature, density, exposure time, and stir rate affect the cleaning efficiency of the $SCCO_2$.

$SCCO_2$ has several environmental, cost, and process benefits. Carbon dioxide is abundant, relatively inexpensive, non-flammable, environmentally friendly, and non-toxic. In addition, CO_2 is recyclable and can be regenerated using a simple distillation process. Without co-solvents, the contaminants are practically the only waste generated by the $SCCO_2$ cleaning process. Thus, waste disposal cost is considerably lower than conventional solvent cleaning methods such as vapor degreasing and aqueous cleaning. $SCCO_2$ cleaning does not require a supplemental drying step because CO_2 exists as gas at ambient conditions [58]. With $SCCO_2$ having very low surface tension, no bubbles nor a meniscus are formed on the surface, resulting in a substrate that is free of residual solvents [70]. However, care must be taken into account throughout the drying step when $SCCO_2$ is evaporated into gas during the decompression cycle. CO_2 expands during evaporation which results to a temperature drop in the system. At low-enough temperatures, water in the vicinity could condense onto the surface of the substrate. Condensation of moisture on the surface can be mitigated by slowing down the decompression process and/or by purging the system with an inert gas during the drying step [70, 60].

$SCCO_2$ is compatible with a wide range of materials including metals and polymers [71, 72, 59, 73, 67]. Cleaning performance of $SCCO_2$ was evaluated on several substrates such as metals, glasses, epoxies, and plastics [59]. Another benefit of $SCCO_2$ is its ability to sterilize materials in addition to contaminant removal from a surface. The sterilizing capability of $SCCO_2$ is a well-documented process [74, 75, 76, 77, 78].

Limitations: Supercritical CO_2 has several drawbacks that must be considered prior to selecting it for precision cleaning applications. The solvating power of nonpolar CO_2 has some limitations. It is not very effective for removing polar, hydrophilic, and ionic compounds. However, the solvating properties of $SCCO_2$ can be enhanced by modifying the density and the chemistry of the fluid which is discussed below. Changing the chemistry of the supercritical fluids is not trivial and requires high-level technical skills [58].

Although the operational and waste disposal cost are lower compared to conventional cleaning systems, building a $SCCO_2$ cleaning infrastructure requires high initial capital. $SCCO_2$ cleaning systems are costly and installation of both cleaning and distillation chambers may require a large footprint [58]. The system also requires heavy-duty and robust chambers that can withstand high-pressure and high-temperature conditions. The system must also be maintained properly and regularly to avoid equipment failure. Because of the operating conditions necessary to achieve the supercritical phase, continuous processing would require sophisticated interlocks that are very costly to implement [58]. Thus, a batch process is typically employed in $SCCO_2$ precision cleaning processes. There are also associated safety risks involved with $SCCO_2$ cleaning. Though CO_2 is nonflammable and nontoxic, it is heavier than O_2 and can create an oxygen deficient atmosphere especially in closed spaces [58]. High operating pressures of $SCCO_2$ also pose safety hazards. Personnel must have proper training and skills for operating such systems. Engineering control, safe operational procedures, and proper precautions such as O_2 monitoring systems must be in place to protect personnel. Additionally, cleanliness verification must be completed with an additional rinse; further development of collecting ‘fluid’ samples for residue and particulate analysis is still required to eliminate the need for external solvent flushes for this final step.

Process Optimization: There are several ways to optimize the cleaning performance of the $SCCO_2$ cleaning process. As discussed in the previous section, the solubility of CO_2 is limited to contamination with low-volatility, low-molecular weight, and nonpolar characteristics. It is not very effective for removing adherent particulates, polar, and ionic compounds. To improve the solvating power of $SCCO_2$, several techniques can be implemented such as incorporating mechanical means to remove adherent particulates, modifying the chemistry of the supercritical fluid, and optimizing the temperature and pressure to achieve desired density. Removal of insoluble particulates that are adherent to the surface can be improved by employing ultrasonics, turbulent flow, convective flow, centrifugal force, and other agitation systems. Centrifugation-based agitation can enhance the cleaning process by providing shear velocity forces to mechanically remove contaminants from the surface [79, 80]. These techniques enhance cleaning rate and throughput. The cleaning performance of $SCCO_2$ can also be enhanced by changing the chemistry of the supercritical fluid by adding polar co-solvents that can dissolve contaminants that have limited solubility in CO_2. Co-solvents such as water [74], dehydrated alcohol [81], surfactants [82], ionic liquids [83], and chelating agents [84] can enhance the solubility of polar, inorganic, and hydrophilic contaminants in $SCCO_2$. It is worth noting that sufficient amounts of co-solvents must be added to maintain the supercritical phase of the fluid [58]. In addition, the compatibility of the cleaning chamber and the co-solvents must be considered prior to the modification of the $SCCO_2$ chemistry.

7.3.1.5 Liquid CO_2 Cleaning

While the cleaning performance of supercritical CO_2 has been previously discussed, the following section focuses on the capabilities of liquid CO_2 as a cleaning medium. A subsequent section will address cryogenic aerosol cleaning, which employs solid-phase CO_2 for effective contaminant removal.

7.3.1.5.1 Cleaning System

LCO_2 cleaning employs liquid phase CO_2 for contaminant removal. It relies on the nonpolar attributes of CO_2 to solubilize hydrocarbons, non-aqueous, and nonpolar compounds. Both LCO_2 and $SCCO_2$ processes utilize the same cleaning infrastructure shown in Figure 21 [58]. The cleaning process for LCO_2 is similar to $SCCO_2$ cleaning and will not be discussed here. The key difference between the two processes is the operating pressure and temperature [57, 59]. CO_2 exists as liquid above the triple point at -57.7 °C and 5.1 atm [27]. Below this pressure, LCO_2 does not exist. The low operating pressure of LCO_2 is a desirable characteristic for cleaning.

7.3.1.5.2 Merits, Limitations, and Process Optimization

The advantages, limitations, and process optimization strategies discussed in $SCCO_2$ cleaning apply to LCO_2 cleaning and will not be extensively discussed in this section. Both $SCCO_2$ and LCO_2 rely on the solubilizing power of carbon dioxide to remove contaminants from the surface. However, both CO_2 phases have different physical and transport properties which can affect the solvating characteristics of the fluid. LCO_2 has higher viscosity, ~0.11 mPa•s at 277 K, and higher surface tension, ~1.5 mN m^{-1}, than $SCCO_2$. This means that wettability and penetrating power of LCO_2 is lower compared to $SCCO_2$. These properties must be considered when cleaning materials with complex geometries. The solvent property of LCO_2 is also attributed to its high density at ~950 kg m^{-3} at 277 K [27]. However, LCO_2 does not have the flexibility of tunable density of $SCCO_2$. Overall, $SCCO_2$ has better wetting, transport, penetrating, and solvent properties than LCO_2. However, the low operating pressures of LCO_2 is desirable because of

lower safety risks. LCO_2 is better suited for materials that are sensitive to high pressure conditions such as safety gears, textiles, clothing, delicate garments, etc.

7.3.1.6 Cryogenic Aerosol Cleaning

Cryogenic aerosol cleaning is a dry-cleaning process that does not utilize liquid medium to remove contaminants from the surface. It uses cryogenic aerosol to dislodge adherent particles through mechanical impact and turbulent lift in the flow stream over the surface [85]. This method is used for cleaning surfaces where solvent cleaning is not feasible due to sensitivity of the materials to organic solvents and aqueous detergents. The method also addresses the limitation of solvent cleaning in which nanometer-sized particles are not effectively removed due to boundary layer effect [86]. Cryogenic aerosol cleaning is employed in the electronics industry to remove contaminants from materials such as semiconductors, integrated circuits, wafers, etc. [87, 86]. It is also used for cleaning vacuum system components, optics, large telescope mirrors, lenses, mass spectrometer components and polymers among others [88, 89].

7.3.1.6.1 Cleaning System and Mechanism

Cleaning Systems: Cryogenic aerosol cleaning system requires an aerosol generator and a cleaning chamber. Aerosols are generated using a specially designed nozzle where inert gases or mixture of gases expand from a high-pressure state to a low-pressure state [85, 90]. Cryogenic aerosols that have been used for precision cleaning include argon-nitrogen (Ar/N_2) mixture, CO_2 snow, and CO_2 pellets.

A schematic diagram of an Ar/N_2 cryoaerosol cleaning system is shown Figure 22 [89]. In this system, a mixture of argon and nitrogen gases are filtered and dried prior to pre-cooling in a cryogenic heat exchanger. The pre-cooled mixture of gases goes through a nozzle where gases expand and form aerosol. In the cleaning chamber, the high velocity aerosol is directed towards the contaminated surface to remove soils [89]. A laminar flow of filtered and dried N_2 purge gas is introduced over the surface to sweep away contaminants. The purge gas also prevents redeposition of contaminants to the surface.

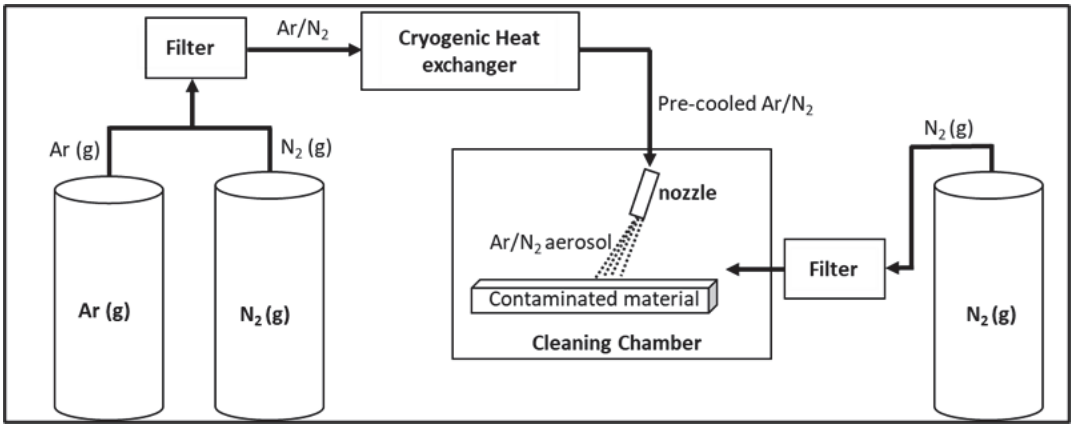


Figure 22. Schematic diagram of Ar/N_2 cryogenic aerosol cleaning system [89].

In CO_2 cryogenic aerosol cleaning, there are two types of CO_2-based aerosols that are used for contaminant removal: CO_2 snow and CO_2 pellets. CO_2 snows are generated from the expansion of either gas phase or liquid phase CO_2 through a nozzle (Figure 23). Gaseous CO_2 and LCO_2 produce 10% and 40% solid CO_2 in the aerosol, respectively [86]. CO_2 snow can be used directly to clean materials, or it can be compressed further into pellets as shown in Figure 23. The CO_2

pellets are then converted into aerosol using the pellet blaster where compressed air accelerates the solid CO_2 to form a jet spray [88]. In the cleaning chamber, either CO_2 snow or CO_2 pellets are introduced at high velocities towards the contaminated surface to dislodge soils. The soils are then swept away from the surface by the gaseous component of the aerosol and the laminar flow stream of inert purge gas. The selection between CO_2 snow and pellets depends on the substrate, contaminants, and the cleaning requirements. Both cryoaerosols offer several advantages and disadvantages. CO_2 pellets are denser and offer a more aggressive cleaning than CO_2 snow. CO_2 pellets are better suited for removing tough adherent particles such as rust, paints, etc. [91]. CO_2 snow lacks the impact energy of the CO_2 pellets, but it minimizes thermal stress to the substrate [88]. Since the CO_2 snow is generated *in situ*, the properties of the aerosol can be modified to accommodate cleaning requirements including addition of co-solvents to enhance removal of polar and inorganic compounds [91].

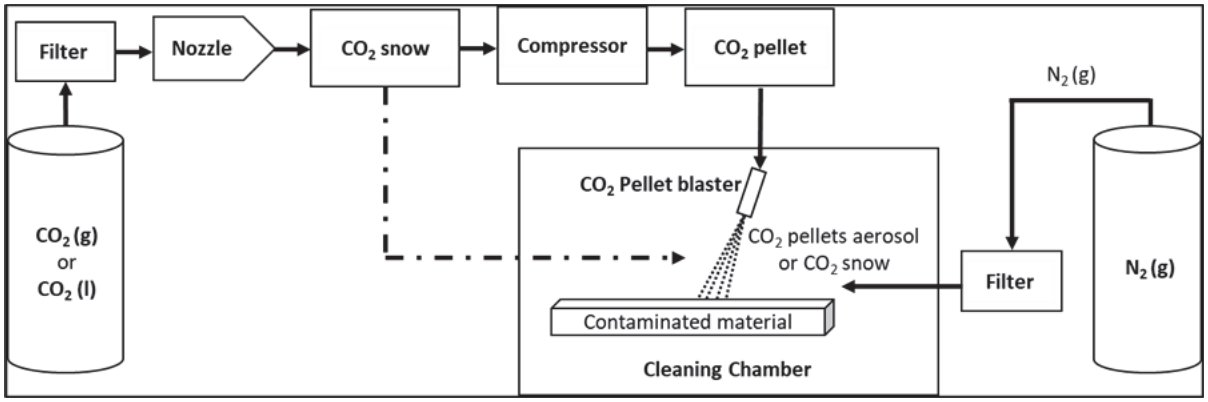


Figure 23. Schematic diagram of CO_2 snow or CO_2 pellet (dry ice blasting) cryogenic aerosol cleaning system [91, 86].

Cleaning Mechanism: Cryoaerosol cleaning removes contaminants from the surface through several mechanisms including energy transfer, micro-explosion/vapor burst, hydrodynamic shear, freeze fracture, reduced adhesion forces, thermophoresis, and thermal shock [89, 91]. The collision between the particle and the contaminants results in a direct transfer of energy and momentum which can overcome the adhesion energy of the contaminant to the surface [89, 88, 88]. As cryogenic particles strike the warmer surface, sublimation of the solid aerosol causes rapid volumetric expansion that results to micro-explosion which can produce sufficient hydrodynamic shear forces to dislodge contaminants [89, 91]. The cryogenic temperature of the aerosol induces cooling to the surface which can result in the freezing of the contaminants, thereby reducing the soil's adhesion force, making it easier to dislodge contaminants from the surface through particle impact and hydrodynamic shear [89, 88].

7.3.1.6.2 Merits, Limitations, and Process Optimization

Merits: Cryogenic aerosol cleaning presents a promising alternative to conventional solvent-based cleaning methods by addressing several of their inherent limitations. This technique employs inert, non-toxic, non-corrosive, and non-flammable gases such Ar, N_2, and CO_2, making it particularly suitable for precision cleaning applications. The favorable environmental profile and widespread availability of these gases further enhance the appeal of this method. Unlike traditional liquid-based cleaning, cryogenic aerosol cleaning is a dry process that does not generate significant liquid waste. Upon impact with the surface, the cryogenic particles sublimate, eliminating the need for a supplemental drying step and thereby reducing both

cleaning time and operational costs. Dislodged contaminants are effectively captured using High Efficiency Particulate Air (HEPA) filtration systems, which also contribute to lower waste disposal [86]. This cleaning method is especially advantageous for materials that are sensitive to solvents or moisture, as it mitigates compatibility issues commonly encountered with traditional solvent cleaning. The cleaning mechanism relies primarily on the physical interaction between cryogenic particles and surface contaminants, rather than chemical dissolution. Furthermore, cryogenic aerosol cleaning is not constrained by the boundary layer effect, which limits the effectiveness of solvent-based methods. As a result, it enables the removal of nanometer-scale particles, making it highly effective for applications requiring ultra-fine particulate removal [86].

Limitations: Cryogenic aerosol cleaning has several limitations. Compared to conventional solvent cleaning, the primary cleaning mechanism of cryogenic aerosol involves physical removal of contamination via mechanical impact between the cryogenic particles and the contaminants. This limits the effectiveness of the cryogenic aerosols in removing chemisorbed contaminants. CO_2-based cryogenic aerosol addresses some of these limitations by enabling the chemical removal of contaminants which will be discussed in the following section.

This cleaning method also requires high-purity gases for aerosol generation and for the laminar flow stream. High purity gases are needed to avoid introduction of new contamination to the surface. These gases need to be dried prior to the cleaning operation because the presence of water can lead to the condensation of moisture on the surface which occurs when the temperature in the system drops due to the expansion of the fluid through the nozzle [86]. In addition, the cryogenic aerosols induce cooling to the surface which can produce thermal shock to the substrate [92]. Thus, it is important to check the compatibility of the material to thermal stress.

Process Optimization: There are several factors that affect the cleaning performance of cryogenic aerosols. These include the nature of the contamination, material properties of the substrate, and aerosol chemistry. Gas purity, moisture, electrostatic charging, and purge gas flow can also influence the cleaning performance.

The material properties of the contamination and the substrate are some of the key considerations when it comes to selecting between Ar/N_2-based and CO_2-based cryogenic aerosols for cleaning. Although Ar solidifies at a much lower temperature than CO_2 and the generation of aerosols is more complex, Ar/N_2 cryogenic aerosol are more suitable for cleaning semiconductor materials due to the availability of extremely high purity Ar gas [89]. In addition, Ar gases are easily desorbed from surfaces because of its relatively high vapor pressure [89]. Ar/N_2 cryogenic aerosol relies on physical interaction for contaminant removal which involves aerodynamic drag force, mechanical impact, and energy transfer between the cryogenic particles and surface contaminant [88]. This presents limitations on its efficacy for removing chemisorbed contaminants. CO_2-based cryogenic aerosol addresses some of these limitations by combining physical and chemical interactions for cleaning. During mechanical impact between the cryogenic CO_2 and the substrate, LCO_2 instantaneously forms on the surface [88, 86]. The solvating properties of LCO_2 enable the dissolution of nonpolar contaminants such as hydrocarbons and greases. However, LCO_2 is not very effective for dissolving inorganic and polar compounds. To address this limitation, the spray chemistry of CO_2 cryogenic aerosol can be modified by adding co-solvents that can dissolve contaminants that are insoluble in CO_2 [91].

Cryogenic aerosol cleaning requires the use of high purity gases for aerosol generation and for laminar flow purging. Gas purification and drying steps are necessary to remove contamination

and moisture in the gas stream. These gases can introduce contaminants that can be deposited onto the surface. Moisture in the system can condense into the surface of the substrate which can lead to corrosion and material degradation. Moisture condensation can be mitigated by performing the operation in dry environment which can be achieved by introducing dry, high-purity gases in a laminar flow over the surface of the substrate. Purge gas flow management is vital in ensuring that contaminants are swept away from the surface and do not redeposit on the substrate [86].

Electrostatic charge management is also important in cryogenic aerosol cleaning. Substrates can get electrostatically charged during cleaning because the process is performed in a dry environment condition [86]. Charged substrate can attract particles that can deposit onto the surface and introduce new contaminants to the substrate [86]. These substrates can also get damaged during electrostatic discharge; hence it is important that electrostatic charging is controlled during the process. Controlling these charges can be achieved by proper grounding of conductive substrates [86]. Charge control can also be performed by using corona bars and radioactive source to neutralize charges on insulating substrates [86].

The aerosol properties such as particle size, density, and velocity can also affect cleaning performance [89, 90]. These properties influence the impact energy and momentum transfer between the cryogenic particles and contaminants. These properties can be controlled by carefully selecting the appropriate nozzle design and spray parameters. The orientation, temperature, and position of the nozzle relative to the surface can be tuned to attain the desired aerosol properties [89].

7.3.1.7 Abrasive Blasting

Abrasive blasting is a method used for cleaning surfaces to remove contaminants such as paints, rusts, etc. It is also used for the preparation and pretreatment of surfaces prior to bonding, painting, and coating [93]. The method utilizes a high-velocity stream of abrasive particles projected into the surface to remove soils. The abrasive particles are propelled through a nozzle by using gases and liquids. However, other abrasive blasting methods such as vacuum blasting and centrifugal blasting do not require propellants for cleaning [94, 95]. The method is similar to cryogenic aerosol cleaning which utilizes solid cryogenic particles that sublimate upon contact with the substrate. Abrasive blasting uses abrasive materials such as volcanic ash, crushed walnuts, almond shells, silica flour, coconut shells, glass beads, crushed eggshells, and sand for blasting [96]. Silica sand is the most commonly used abrasive material used for cleaning, hence abrasive blasting is also known as sand blasting. [97].

7.3.1.7.1 Cleaning System and Mechanism

The abrasive blasting method requires a specially designed nozzle to propel abrasive materials using a compressed air or liquid propellant as shown in Figure 24. In wet abrasive blast cleaning, the abrasive is injected into a water stream for cleaning which suppresses dust production [95]. Abrasive blasting can be performed in an open-space, blast cabinet, or blast room. Blast cabinets and blast rooms are containment structures to prevent environmental release of hazardous dusts and abrasive particles. Blast cabinets and room also offer a closed-loop process allowing the abrasive particles to be collected, recycled, and reused for the next cleaning cycle.

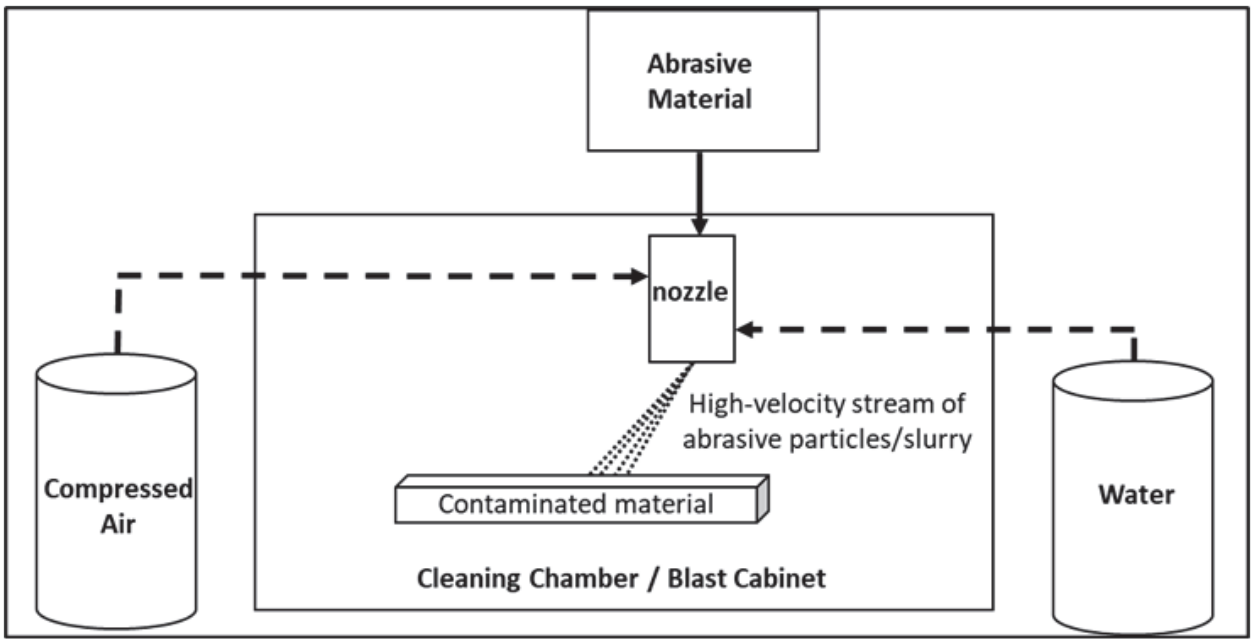


Figure 24. Schematic diagram of an abrasive blasting cleaning system.

7.3.1.7.2 Merits, Limitations, and Process Optimization

Merits: Abrasive blasting is widely available, and its scalability makes it an attractive method for cleaning surfaces of large structures. It is used for removing paints and coatings from highway bridges, storage tanks, ships, and other large infrastructures [95]. It is also used for removing rust and oxide layer from metallic components. The method can be tailored so that the abrasive materials are recycled and reused which makes the process cost effective [98].

Abrasive blasting is a common surface pre-treatment technique that is used to clean and prepare substrates prior to bonding, repainting, and recoating [95, 93]. It is used to modify the surface properties of materials to achieve the desired morphology which impacts the interaction-related features of material [98]. Morphology influences the adhesion performance of coatings to surfaces [99]. Surface pre-treatment is also an important step for structural bonding applications where two materials are joined together using adhesives [93]. Surface pre-treatment is vital in enhancing the adhesion properties of the surface prior to bonding [93]. It can also be to passivate the surface to enhance corrosion resistance of steel [100] and to enhance the adhesion properties between two materials.

Limitations: Abrasive blasting poses several safety and environmental hazards that must be carefully managed to ensure safe operation. The process generates a substantial amount of airborne dust originating from the abrasive media, dislodged contaminants, and abraded substrate materials [97]. This respirable dust may contain hazardous substances such as crystalline silica, lead, chromates, and other toxic compounds. Additionally, the high-velocity stream of abrasive particles presents a risk of physical injury to operators and nearby personnel, further emphasizing the need for stringent safety protocols [97]. Moreover, dusts produced from the process can pollute the environment and deposit on surrounding materials and infrastructures [96]. To mitigate these risks, comprehensive safety measures including the use of appropriate PPE, engineering controls, and thorough personnel training are essential for maintaining a safe and compliant working environment. While wet blasting methods mitigate many of the health risks

associated with airborne dust exposure, they introduce other operational challenges. Specifically, the process can result in the deposition of a slurry composed of abrasive materials on the ground, which can take some time to dry [96]. Additionally, water used in the process can infiltrate porous materials and remain on surfaces, potentially leading to corrosion or material degradation over time.

Abrasive blasting, in general, is an aggressive cleaning technique that removes contaminants such as dirt, paint, rust, and coatings by physically abrading the surface with a high-velocity stream of abrasive particles. This inherently destructive process can also erode the substrate itself, potentially causing irreversible damage [96]. As a result, abrasive blasting is not suitable for cleaning delicate materials or components with intricate features. In addition, this technique is not suitable for cleaning hard-to-reach surfaces of materials with complex geometries.

Process Optimizations: The performance of abrasive blasting is affected by several factors such as blasting parameters as well as the properties of the abrasive particles and contaminated material. Blasting parameters such as pressure, angle, distance, duration, and the abrasive particle can affect cleaning performance and surface pre-treatment [93]. These parameters are optimized depending on the rigidity and surface properties of the substrate [93]. The effect of abrasive blasting on surface morphology depends on the substrate [98]. Surface morphology affects the wettability and adhesion performance of the material [101]. Process condition must be optimized to achieve the desired surface finish and to minimize substrate damage.

7.3.1.8 Laser Cleaning

Laser cleaning is a form of laser ablation technique that uses a high-energy light beam to remove contaminants from the surface of materials. This cleaning process uses short pulses of a laser beam that can be focused and controlled to selectively clean areas of interest. In this manner, it can provide a highly direct cleaning operation and exclude any sensitive areas that do not require cleaning [102].

7.3.1.8.1 Cleaning Systems and Mechanisms

There are multiple methods that utilize pulsed laser for cleaning surfaces. These include dry laser cleaning, wet/steam laser cleaning, and laser-shock wave cleaning. Mechanisms involved in each cleaning process are discussed below.

Dry Laser Cleaning: Dry laser cleaning is the most widely used laser cleaning process [103]. It uses a laser to evaporate rust and other contaminants from the surface of materials by directing a focused laser beam onto a targeted area to ablate unwanted material. When aimed at a metal surface, the dirt layer and any oxides underneath will absorb the laser energy and evaporate. The metal underneath will not absorb the laser energy leaving nothing but a clean surface that is ready for welding and painting. It is much faster than other rust removal methods and works well on irregular surfaces that are difficult to clean with abrasive methods. It can be applied manually as well as robotically. The system uses short pulses of laser light producing micro-plasma bursts along with thermal pressure and shock waves to sublimate the rust and separate it from the metal without damaging the metal. Material removal is halted when the laser is applied to a clean surface because it only sublimates the rust and contaminants. The device can be set for a certain depth to skim away surface rust, paint, and filler leaving a prepared surface. Surfaces such as steel, aluminum, and copper will usually remain cool without any significant heating or warpage of the material. Angular laser cleaning techniques have been developed that irradiate the

contaminant surface at a glancing angle. This is claimed to drastically improve the cleaning efficiency by at least 10 times compared to typical laser cleaning that uses perpendicular irradiation [104, 105].

Wet/Steam Laser Cleaning: Wet/Steam laser cleaning (WLC) uses a liquid layer that strongly absorbs the laser wavelength being used. The laser irradiation can rapidly heat and evaporate the liquid, and this can force particles from the surface [106]. Alternatively, the workpiece may be kept in an atmosphere of enhanced humidity, which results in capillary-condensed water [107]. Steam laser cleaning uses a very thin liquid layer, which is condensed onto the substrate surface. The liquid layer is superheated (and evaporated) and causes the nucleation. This results in high pressure below the contaminant. The wet laser cleaning process uses shock pressure to remove the contaminants, which in some cases can be higher than the thermodynamic critical pressure. Efficacy has been demonstrated for the removal of microparticles from a bulk surface [108]. The main driver of development of laser cleaning, particularly the water-assisted method, has been the semiconductor industry, where the cleaning of silicon wafers from sub-micrometer particles became a problem in the course of diminishing feature size. WLC can be used selectively to clean only the contaminated areas. Both dry and steam cleaning are able to remove submicron particles from solid surfaces, but the steam-assisted process needs lower laser fluences and is able to remove smaller particles [109]. Steam-assisted laser cleaning is virtually a dry process capable of removing particles down to 60 nm in diameter. Other conventional methods of particulate removal from silicon wafer surfaces are ineffective for particles less than 0.2 μm - 1 μm [110].

Laser Shock Wave Cleaning: Laser shock cleaning (LSC) uses a high-intensity laser focused onto a tight spot slightly above the sample to be cleaned. The laser-induced breakdown (LIB) of the gas produces a strong shock pressure wave, which impinges onto the surface of the substrate. It has been shown that laser shock cleaning is effective for removing nanoparticles [111]. LSC can also be used with micrometer-sized water droplets producing a high-speed jet (with speeds up to 1600 m/s), which removes particle contaminants from substrates [112]. LSC can be used to relieve tensile surface stresses in the surface substrate and are further discussed in the following section.

Cleaning Systems: The basic design of a laser cleaning system generally incorporates a control panel to adjust the power on the laser unit, as well as other settings, so the laser can be used on various substrates without damaging the material. The system incorporates air and water chiller components to control the temperature of the unit. Units are also equipped with built-in suction unit at the hand-held cleaning head to vent the sublimated fumes away from the operator. The laser units come in various sizes from 20 W to 3000 W. Smaller portable units can weigh as little as five pounds but are only feasible to use for very small cleaning projects; larger portable units can weigh several hundred pounds. Larger stationary units that are robotically controlled are also available and are often used in industrial settings that require high production rates.

7.3.1.8.2 Merits, Limitations, and Process Optimization

Merits: Laser cleaning is a versatile method that enables dry cleaning a broad range of materials such as metals, thermoplastics, composites, stone, wood, and concrete. It can also be used for various applications such as rust removal, contaminant removal, laser welding applications, carbon fiber-reinforced polymers, and thermal stress relief. Laser removal of contamination is much safer and more environmentally friendly process than wet removal methods that use

corrosive chemicals and solvents or sand blasting methods which can increase the risk of silicosis. Most units come with a ventilation system that removes sublimated vapors away from the operator preventing hazardous exposure of contaminants to personnel. It does not require toxic chemicals for cleaning, so hazardous waste generation is minimized, and disposal cost is reduced. Also, the process does not require pre-treatment and post clean-up of materials.

Laser cleaning offers a relatively fast and high-throughput cleaning process. Cleaning times may be reduced up to 20-fold when compared to other surface cleaning treatments [113]. Smaller 20W to 100W units can clean 10 to 30 square feet of material per hour; 100W to 300W units can clean 30 to 80 square feet of material per hour; and 500W to 3000W units can clean from 100 to more than 200 square feet of material per hour.

Limitations: Laser cleaning systems can be costly and require high initial capital, ranging from $200 to 500K. Cost will be higher for units that can be operated robotically. The initial investment may be high, but it offers long-term benefits and returns because the process does not utilize toxic solvents, which can be costly to dispose of. Laser cleaning is used to primarily clean external surfaces and is unable to reach small internal surfaces. An internal volume must be large enough and accessible to be laser cleaned. Laser cleaning is not suitable for cleaning materials with complex geometries that have deep crevices and blind holes.

Laser cleaning is sensitive to operational and process parameters. The type of laser cleaning process and operational parameters depends on the material properties of substrate and the contaminant. If not performed properly, dry laser cleaning may result in material damage, change in surface chemistry, microstructure, etc. Nondestructive decontamination has not been completely realized by dry laser cleaning [103]. Hence, it is necessary to optimize laser parameters to avoid surface damage, substrate oxidation, etc. Cleaning performance may be influenced by the surrounding atmospheric environment including exposure to air, N_2, Ar, or vacuum environments [113]. Dry laser cleaning can lead to a progressive buildup of decomposition products on the surface which decreases cleaning efficiency [113].

Engineering control and safety precautions must be established to prevent damage to the eyes and skin. Enclosed areas with interlocking doors are preferred to prevent accidental laser exposure to operators and anyone nearby. Laser should be used at specified distances away from unprotected workers.

Process Optimization: The ability of laser cleaning to remove contaminants from surfaces depends on several factors including the type of laser cleaning method, laser parameters, and the material properties of the contaminants, substrate, and solvents used during laser irradiation [113]. The intensity of the laser should be strong enough to produce the desired cleaning effect, but not strong enough to damage the substrate. The type of laser cleaning method (e.g., dry vs liquid-assisted laser cleaning) must be selected based on the application. The laser parameters such as the angle of incidence, front or rear irradiation, the laser fluence, the number of pulses used, the choice of wavelength, and pulse length must be optimized for the cleaning application [114]. When using liquids in the cleaning process, they should be compatible with the substrate and produce the desired pressure when superheated by the laser to remove the contaminants.

7.3.1.9 Plasma Cleaning

Plasma, considered the fourth state of matter, is a quasi-neutral gas consisting of freely moving positively charged ions, electrons, and neutral species [115]. Depending on the temperature

generated in the system and the degree of ionization, man-made plasma can either be classified as thermal or nonthermal [115]. Thermal plasma, also known as hot or equilibrium plasma, is typically fully ionized plasma in which the electron temperature is equal to the thermodynamic temperature [115]. Nonthermal plasma, also known as cold or non-equilibrium plasma, is generated near ambient temperature and only a fraction of the gas is ionized [115]. Non-thermal plasma is generally used for surface cleaning applications because it yields minimal damage to the surface. Plasma cleaning is a dry-cleaning process and can also be used to prepare and activate the surface of materials for coating and bonding applications. In addition, plasma treatment can be used to passivate the surface of a material by forming a thick oxide layer on the substrate [116].

7.3.1.9.1 Cleaning System and Mechanism

A schematic diagram of a typical plasma cleaning system is available in previously published literature and will not be reproduced in this report [115, 117, 118]. In this cleaning process, contaminated materials are placed inside a vacuum chamber, which is evacuated to a predetermined pressure level. Once the desired vacuum conditions are achieved, a process gas, commonly argon, hydrogen, oxygen, nitrogen, or filtered breathing air, is introduced into the chamber to initiate plasma generation [119, 117]. The contaminated components are then exposed to the plasma for a specified duration, during which surface contaminants are effectively removed through physical and chemical interactions. The vacuum environment facilitates the efficient removal of dislodged contaminants by sweeping them away from the substrate surface, thereby minimizing the risk of redeposition and ensuring a cleaner final surface.

As mentioned, plasma cleaning is a surface decontamination technique that utilizes energetic species including electrons, ions, photons, radicals, and reactive neutral particles that are generated within a plasma discharge to remove contaminants from material surfaces [120]. These energetic particles are produced through ionization and excitation processes that occur during non-elastic collisions within the discharge gas, which may include argon, oxygen, hydrogen, or other suitable gas [115]. As the excited species return to lower energy states, they release energy in the form of photons, contributing to the overall reactivity of the plasma. The interaction between these reactive species and the substrate surface occurs through both physical and chemical mechanisms. Depending on the gas composition and process parameters, plasma-surface interactions can result in surface ablation, activation, deposition, or grafting [115].

Plasma ablation involves mechanical removal of contaminants by the reactive particles which attack the surface to initiate sputtering, photodecomposition, and thermal evaporation of weakly bonded organic contamination [120, 115]. Collision between the energetic species and the contaminants leads to transfer of energy which can be sufficient to dislodge contaminants from the surface [118]. These impinging particles can also provide enough energy to break molecular bonds leading to the decomposition of contaminants [118]. The reactive particles from the plasma are generally hot and can dissipate their energy to increase surface temperature which enhances chemical interactions with the contamination [120]. Additionally, plasma can facilitate chemical reactions to decontaminate surfaces. Depending on the gas composition, plasma-induced chemical reactions can lead to the degradation of contaminants via the oxidation and/or reduction reaction.

7.3.1.9.2 Merits, Limitations, and Process Optimization

Merits: Plasma treatment presents several advantages for precision cleaning. Plasma cleaning has demonstrated excellent performance for decontaminating surfaces [117, 121]. It offers a non-contact and non-destructive approach for cleaning [118] and is a simple cleaning operation that is reliable, flexible, and versatile. This technology can be used for cleaning, sterilization, activation, passivation, and other surface pre-treatment processes [115]. Plasma generation and engineering is generally reliable and reproducible [115]. Plasma can penetrate through fine pores which enables cleaning of materials with intricate and complex geometries.

Plasma gas and operational parameters can be modified and tuned depending on the desired surface treatment result. Plasma generated from breathing air has shown excellent cleaning performance [117]. Breathing air is abundant and its wide availability eliminates the need for consumables, thereby making the process cost efficient.

Plasma treatment is considered an environmentally friendly process because it does not require solvents for cleaning. It minimizes generation of waste stream which reduces waste disposal and remediation cost. The process also reduces environmental liability and risks for material obsolescence [121]. The method does not require a drying step which also decreases cleaning time and operational cost. However, it is important to note that cleaning time also depends on the contamination level [121].

Limitations: There are several challenges that must be addressed and mitigated to ensure that desired cleaning performance is achieved. Plasma cleaning is effective for removing moderate layer of contaminants on surfaces. Heavily soiled materials may need to be pre-treated prior to plasma cleaning. As plasma cannot penetrate far into holes/crevices, components with complex geometries and internal cleaning requirements cannot be accurately cleaned by this process. Additionally, cleaning efficiency depends on the plasma gas chemistry and optimized cleaning parameters which will be discussed in the next section. These parameters must be optimized to prevent irreversible surface damage and modification [115] and to ensure uniform plasma distribution across the surface of the substrate [122].

There are cost considerations in selecting plasma-based approach for cleaning. Systems can be costly and require high initial capital. In addition, plasma generation and maintaining vacuum pressure is an energy intensive process. The equipment must be carefully and regularly maintained to ensure consistent operation. Process control and monitoring systems are important in maintaining the operational parameters.

Process Optimization: There are several factors that affect the performance of plasma cleaning. These include plasma chemistry, gas pressure, discharge power, exposure time, and working distance [117, 118]. It is important to select the appropriate plasma composition and operational parameters to ensure a damage-free cleaning process.

The chemical composition of the plasma affects cleaning efficiency. A single-component gas or mixture of gases can be used to generate plasma. Gases such as Ar, He, Molecular Deuterium (D_2), H_2, O_2, N_2, etc., have been evaluated for plasma cleaning [118]. In addition, multi-component gases such as H_2/Ar/Ne, Ar/O_2, N_2/O_2, and breathing air, etc., have been employed in plasma cleaning [118, 117]. Selection of process gas or mixed gas depends on the material being cleaned, the nature of contaminants, and the desired surface treatment outcome. Plasma composition affects surface interactions between the energetic particles and contaminants. In

some plasma, physical interaction is the main mechanism for cleaning surfaces. For example, argon plasma primarily relies on energy transfer for mechanical removal of contaminants. Some plasma employs reactive gases to enable chemical reactions such as oxidative and reductive decomposition of contaminants to clean surfaces. In some cases, a multi-component gas is employed to generate plasma to remove stubborn and complex contamination [118].

Cleaning efficiency is also affected by gas pressure which influences the gas and plasma density [118]. The higher the pressure, the higher the plasma density which increases the cleaning intensity, thereby leading to higher cleaning efficiency [118]. However, too much pressure can have a negative effect on the cleaning performance, leading to an unstable plasma density. Discharge input power affects the performance of plasma cleaning. The higher the input power, the more gases are ionized, which leads to formation of more reactive radicals in the plasma [118]. This results in an increase in plasma density and ion flux, thereby enhancing the cleaning performance. However, increasing the input power can raise plasma temperature which could negatively affect heat-sensitive materials [118].

Cleaning duration is an important factor that must be considered in plasma cleaning. Interaction between the plasma and the contaminants requires sufficient time to effectively remove impurities from the surface. Generally, cleaning efficiency is enhanced with increasing cleaning duration. However, increasing the cleaning cycle can increase energy consumption and decrease throughput [118]. In addition, longer exposure time with the plasma can raise the temperature of the substrate which can result in material damage. The distance between the plasma spray gun and the substrate must also be optimized to enhance the efficiency of plasma cleaning. Too much distance can decrease the plasma density which results in a decrease in the concentration and kinetic energy of reactive particles, thereby reducing the chemical and physical interaction between the plasma and the impurities. Too close of a gap can result in thermal stress on the substrate.

7.3.1.10 Ultraviolet-Ozone Cleaning

Ultraviolet-ozone (UV-O_3) cleaning technology is a dry-cleaning process that employs UV-assisted photosensitized oxidation reactions to break down organic molecules [123, 124]. UV radiation has been known to decompose organic compounds; UV-assisted chemical breakdown converts contaminants into gaseous volatile products that desorb from the surface, thus facilitating contaminant removal [125]. UV-O_3 cleaning is also used for sterilization and modification of surfaces for subsequent processes such as bonding, coating, etc. [126]. Moreover, it can be used for removal of radioactive contamination such as tritium [126]. UV-O_3 cleaning has been used to remove a wide range of contaminants from various substrates including ceramic materials, semiconductor wafers, carbon nanotubes, fabrics, polyimide composites, glass plates, polymer, and metals such as aluminum alloys, stainless steel, nickel, etc. [126]. This cleaning method demonstrated removal of contaminants such as cutting oils, human skin oils, silicone oils and greases, vacuum pump oils, beeswax, cleaning solvent residues, and microbial contaminants [123, 126].

7.3.1.10.1 Cleaning System and Mechanism

Cleaning System: UV-O_3 cleaning systems are commercially available and can be purchased in various sizes [126]. An example schematic diagram is shown in Figure 25. The contaminated materials are placed in the cleaning chamber which is equipped with UV sources such as low-pressure mercury lamps that can emit radiation at 184.9 nm and 253.7 nm [127]. The system can

also be equipped with an excimer emission source, such as xenon lamps, that emits vacuum UV (VUV) radiation at 172 nm [127]. These wavelengths induce photochemical reactions that convert molecular oxygen (air) into ozone and atomic oxygen. Even though ozone is generated during UV irradiation, cleaning systems are also equipped with ozone generator to provide sufficient ozone to the chamber to enhance the cleaning efficiency [126, 124]. After UV irradiation and cleaning, the chamber is purged with nitrogen to remove all the process gases [126].

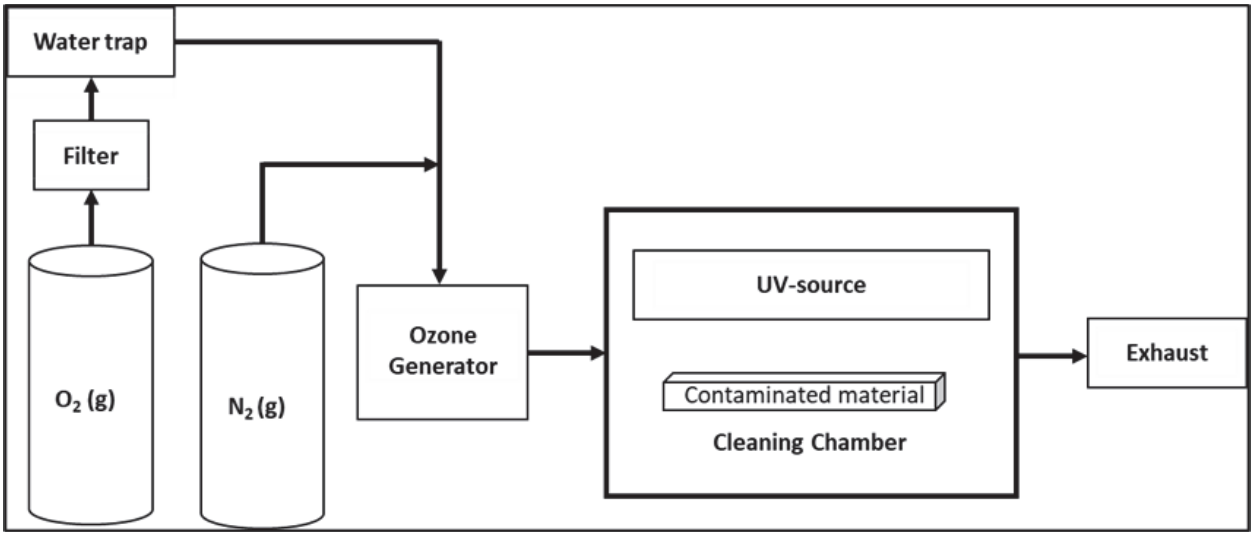


Figure 25. Schematic diagram of UV-O_3 cleaning system [124].

Cleaning Mechanism: The UV-O_3 cleaning method employs a photosensitized oxidation process that involves multiple chemical reactions that occur simultaneously to decontaminate surfaces [123, 126]. The process involves treatment of samples with UV radiation resulting in the chemical reactions described in Equation 1, Equation 2, and Equation 3. Molecular oxygen (O_2) absorbs UV radiation at 184.9 nm and generates atomic oxygen (O*) which can then react with molecular oxygen to produce ozone (O_3) as shown in Equation 1 and Equation 2 [126]. Ozone then absorbs UV radiation at 253.7 nm and forms atomic oxygen which is a strong oxidizing agent (Equation 3) [126]. It is important to note that molecular oxygen does not absorb radiation at 253.7 nm [123]. Simultaneously, organic contaminants absorb both radiations at 184.9 nm and 253.7 nm, resulting in chemical breakdown that leads to the formation of decomposition products such as ions and free radicals as well as excited and neutral molecules [126]. These decomposition species then react with atomic oxygen to form volatile compounds such as CO_2 and water vapor, which then desorb from the surface [123].

Equation 1. $$\boldsymbol{O_2 + h\nu\,(184.9nm) \rightarrow O^* + O^*}$$ [126]

Equation 2. $$\boldsymbol{O^* + O_2 \rightarrow O_3}$$

Equation 3. $$\boldsymbol{O_3 + h\nu\,(253.7nm) \rightarrow O^* + O_2}$$

Alternatively, an excimer emission source that emits UV radiation at 172 nm can be used for cleaning. Molecular oxygen strongly absorbs radiation at 172 nm which is transparent to nitrogen [127]. At this wavelength, atomic oxygen and ozone can be produced in oxygen or air at higher efficiency than at 184.9/253.7 nm [127]. Thus, improving the cleaning rate and efficiency of the UV-O_3 treatment. These same photochemical reactions described above are responsible for the

cleaning mechanisms at 172 nm in which contaminants are ultimately converted to gaseous products.

7.3.1.10.2 Merits, Limitations, and Process Optimization

Merits: UV-O_3 cleaning technologies offer several advantages in terms of cost efficiency and environmental impact. It is a simple and convenient process that is inexpensive to set-up [123, 125]. The cleaning unit utilizes cold UV sources that do not require an additional cooling system, thereby reducing energy consumption [126]. The method supports high-throughput cleaning, with surface decontamination achievable in under one minute under optimal conditions [123]. As a dry process, UV-O_3 cleaning does not rely on liquid solvents, eliminating the need for a drying step and significantly reducing waste generation and associated disposal costs. UV-O_3 cleaning offers a milder cleaning approach when compared to other dry oxidative cleaning techniques such as plasma cleaning [125] as it does not utilize reactive species with high kinetic energies such as ions, protons, electrons, and radicals for contaminant removal [125]. It can also be performed under atmospheric pressure which makes the process more cost efficient [125].

This method has been used to clean a wide range of substrate to remove a variety of contaminants such as soldering fluxes, cutting oils, vacuum pump oils, silicone diffusion pump oil and vacuum greases, carbon films, etc. [126]. The technique has also been employed in surface preparation for coating and bonding applications across various materials, including semiconductor wafers, ceramics, polyimide composites, fabrics, carbon nanotubes, and metals such as stainless steel, aluminum alloys, platinum-iridium alloys, copper, and gold [126]. Additionally, it has been used to clean polymeric materials such as polyethylene, polystyrene, poly(vinyl chloride), poly(dimethylsiloxane), and poly(ether ketone), demonstrating its versatility and effectiveness across diverse material systems [126].

Limitations: The UV-O_3 cleaning process is not intended for removal of gross contamination [126]. This method is applicable for final cleaning of substrates. Generally, pre-cleaning of substrates is required prior to UV-O_3 treatment [124]. Contaminants such as particles, metals, and inorganic salts that are not decomposed to volatile products by UV-O_3 treatment must be removed before cleaning. Pre-cleaning can be performed using a sequence of acetone, methanol, and DI water [126]. It should be noted that bases, acids, chlorinated and fluorinated fumes are not introduced into the cleaning chamber to prevent corrosion and damage to the system including the materials to be cleaned [126]. Materials compatibility can limit the feasibility of UV-O_3 for cleaning. Materials such as plastics can degrade in the presence of UV radiation and ozone [126]. Prolonged exposure to UV and improper use of UV wavelength can lead to the degradation and corrosion of materials.

UV exposure can result in serious eye and skin injuries, thus it is important that personnel should wear PPE during operation [123]. Engineering controls, such as safety interlocks, must be incorporated to the UV-O_3 system to avoid accidental UV exposure. The system should be completely enclosed during operation and must also integrate safety interlocks that automatically shut the UV lamp off every time the system is opened. Another safety hazard associated with this process is the exposure to ozone which is a highly toxic gas [124]. UV-O_3 cleaning facility must include a monitoring system to ensure that personnel are not exposed to ozone and the cleaning system must incorporate an automatic venting system that is connected to the door interlock so inert gases are automatically used to purge the ozone out of the chamber [126]. In addition to

health risks, ozone is also a highly dangerous gas in a cryopump vacuum system because it can become explosive at certain conditions [124].

Process Optimization: The cleaning performance of UV-O_3 can be influenced by several factors such as UV wavelength and intensity, UV exposure time, composition of feed gas, gas flow rate, and substrate temperature [123, 125]. The wavelength used for UV irradiation is an important parameter in the cleaning process as was described above. UV intensity can also affect the cleaning performance; it can be controlled by changing the distance between the substrate and the UV source. Cleaning rate is impacted by exposure time to the UV radiation. While a faster cleaning time limits the exposure of the substrate to the UV radiation and thus level of cleaning, some materials such as oxide-forming metals, can get corroded and oxidized when exposed to UV for an extended period [123].

The composition and flow rate of the feed gas can also affect the cleaning performance of the process. Faster cleaning can be achieved by supplying a sufficient amount of molecular oxygen at an optimal flow rate to ensure high concentrations of atomic oxygen and ozone are generated in the system [125]. Atmospheric gases can positively or negatively influence the UV-O_3 method. For example, dropwise addition of distilled water or hydrogen peroxide can enhance the cleaning rate [124], but some impurities in air can result in corrosion of metallic substrates. It is important to optimize the cleaning parameters including the substrate temperature to maximize the cleaning performance of UV-O_3 treatment.

7.3.1.11 State-of-the-Art Precision Cleaning Technology Summary

Precision cleaning is a critical process across a wide range of industries, including aerospace, defense, manufacturing, medical devices, electronics, and semiconductors. It plays a vital role in ensuring the quality, performance, reliability, safety, and regulatory compliance of components and systems. Several precision cleaning technologies were highlighted in this report including their advantages, limitations, and cleaning mechanisms. It is important to tailor and optimize the operational parameters of these processes to achieve the desired cleaning performance and cleanliness level. There are several key considerations when selecting precision cleaning process for surface decontamination. These include: (1) cleaning performance; (2) ability to perform cleanliness validation without additional rinse steps; (3) environmental impact and regulatory risk; (4) safety and health risks; (5) facility requirement; (6) scalability; and (7) operational cost.

7.3.1.11.1 Cleaning Performance and Mechanism

Precision cleaning is a critical process in the preparation of materials and components, particularly in high-reliability applications. It involves the removal of contaminants through physical interaction and/or chemical reactions that overcome the adhesion forces binding contaminants to surfaces. Most cleaning methods integrate both chemical and physical mechanisms to effectively eliminate a broad spectrum of contaminants, as the ones summarized in Table 11. The suitability of a particular cleaning process depends on several factors, including the physical and chemical properties of the contamination, the characteristics of the cleaning medium, and the nature of the substrate. Selecting an appropriate cleaning method is essential to achieving the desired level of cleanliness and meeting specific surface treatment objectives. It is important to note that certain cleaning techniques are not designed to remove gross contamination. For example, UV-ozone cleaning requires pre-treated surfaces to effectively remove contaminants. In many cases, a combination of cleaning processes is employed to achieve the desired level of cleanliness.

Chemical-assisted cleaning processes rely on the chemical reactions between the contaminants and the cleaning medium, which may include chemical solvents, plasma, and UV-ozone. The effectiveness of chemical cleaning depends on selecting a medium that can dissolve or decompose the contaminants without reacting adversely with the substrate. Solvent-based cleaning relies on the solubility of the contaminants, which is influenced by molecular properties such as polarity, ionic character, and fluorination. Aqueous solutions are particularly effective for dissolving ionic and polar contaminants, while carbon dioxide-based media and nonpolar organic solvents are better suited for nonpolar contaminants. Fluorinated solvents are especially effective for removing fluorinated greases. In some cases, mixtures of solvents are used to enhance the dissolution process. Plasma and UV-ozone cleaning, on the other hand, function through oxidation and/or reduction reactions that chemically decompose contaminants. Plasma cleaning utilizes energetic particles including electrons, ions, photons, radicals, and reactive neutral species to induce photodecomposition and molecular breakdown of surface contaminants. UV-ozone cleaning employs ozone and UV-assisted photosensitized oxidation reactions to convert organic molecules into volatile byproducts.

Physically-assisted cleaning methods remove contaminants through mechanical or physical forces. These methods are often used in conjunction with chemical cleaning to enhance overall effectiveness. Liquid-based cleaning systems, such as those using solvents, aqueous solutions, supercritical fluids, or liquid carbon dioxide, typically incorporate mechanical agitation, ultrasonic systems, or fluid motion to dislodge insoluble particulates from surfaces. Agitation and turbulent fluid flow generate shear forces that help remove contaminants. Sonic cleaning introduces acoustic energy, which facilitates contaminant removal through acoustic streaming and cavitation. More aggressive techniques, such as abrasive blasting, use high-velocity streams of abrasive particles to physically strip contaminants from surfaces. Laser cleaning employs focused laser energy to thermally ablate or sublimate contaminants. Plasma cleaning also contributes to physical cleaning through ablation, sputtering, and thermal evaporation, driven by the interaction of energetic and reactive species with the surface.

7.3.1.11.2 Cleanliness Verification

The critical final step in precision cleaning is verifying the component that has been cleaned meets the required cleanliness level, both from a residue and particulate perspective. Of the alternative processes discussed in this section, many carry the limitation that additional rinses or significant additional system design is required to eliminate the need for separate, final rinse procedures to evaluate cleanliness levels. Without also addressing solutions to this step of the cleaning process, facilities would likely still have dependence on solvents at risk for discontinuation and/or regulation.

7.3.1.11.3 Environmental Impact and Regulatory Risk

While precision cleaning is a critical process in many industrial applications, it also presents notable environmental and regulatory challenges. Cleaning operations must account for their environmental footprint, particularly in terms of energy consumption, hazardous waste generation, and the use of chemical solvents and other cleaning media. These factors must be carefully managed to ensure compliance with environmental regulations and to minimize ecological impact.

Energy Expenditure: One of the primary environmental considerations in precision cleaning is energy expenditure. Cleaning systems often require substantial energy inputs to support

operations such as heating, cooling, pumping, sonication, agitation, drying, robotic automation, and the movement of components via conveyors or other transfer mechanisms. These energy demands can be mitigated through regular maintenance of cleaning equipment, the integration of renewable energy sources, and the optimization of process parameters. Processes that utilize chemical solvents, aqueous solutions, supercritical fluids, or liquid carbon dioxide (LCO_2) typically require heating to enhance cleaning performance. However, heating is energy-intensive, and it is essential to optimize operating temperatures to reduce energy consumption. Additional energy demands may arise from fluid and gas circulation pumps, cooling systems for laser units, laser operation itself, cryogenic heat exchangers for pre-cooling gases such as argon and nitrogen, pressure systems for gas compression into supercritical phases, decompression units, cryogenic aerosol nozzles, robotic automation systems, plasma generation, vacuum maintenance, and ultraviolet (UV) light generation (Table 12).

Aqueous cleaning is an energy-intensive cleaning method due to its multi-step process, which typically includes pre-washing, ultrasonic cleaning, rinsing, and drying. This method requires relatively higher temperatures than solvent-based cleaning and heating large-scale aqueous baths can be both time-consuming and costly. In some cases, it is more energy-efficient to maintain the bath at its optimal operating temperature continuously, even when not in active use, to avoid the high energy cost and operational delays associated with reheating. Standby power consumption must therefore be factored into the overall energy budget. Additional energy is also consumed by pumps used to circulate cleaning solutions and by ultrasonic systems that accelerate contaminant removal. The rinsing phase, often enhanced with ultrasonic agitation, is critical for removing residual solvents. Furthermore, drying steps which include employing heat, vacuum, or inert gases are necessary to prevent corrosion or degradation of sensitive substrates, further contributing to the process's energy demands.

Environmental Impacts of Chemical Solvents and Cleaning Mediums: In addition to energy use, the environmental impact of chemical solvents and cleaning media must be carefully evaluated. These impacts are assessed based on their potential to pollute air, water, and soil, as well as their ecological toxicity, persistence, degradability, and bioaccumulative potential (Table 12). Cleaning agents are subject to regulatory scrutiny based on properties such as ODP, GWP, flammability, toxicity, exposure risk, and other safety considerations.

Traditional cleaning methods, such as vapor degreasing with fluorinated or organic solvents, have been significantly affected by these regulations. Some solvents have been banned, placed under strict regulatory control, or are at risk of obsolescence. For example, CFCs like Freon 113 have been phased out due to their high ODP. Other solvents, including chlorobromomethane, dibromomethane, and HCFC-141b, are no longer acceptable for precision cleaning [43]. Solvents such as heptafluorocyclopentane, perfluorobutyl iodide (PFBI), trans-1-chloro-3,3,3-trifluoroprop-1-ene (Solstice 1233zd(E)), and trans-1,2-dichloroethylene are subject to workplace exposure limits and safety standards [43]. Additionally, (PFAS)-based solvents like Novec HFE-7100 are facing supply chain risks due to manufacturing phase-outs [42]. Comprehensive documentation is available listing acceptable solvents for precision cleaning, including their ODP, GWP, flammability, exposure limits, and safety guidelines [43]. These resources also provide information on aqueous and semi-aqueous cleaners, supercritical fluids, plasma, and UV-ozone cleaning technologies.

In response to the environmental risks associated with solvent-based cleaning, alternative methods have been developed. Aqueous, LCO_2, supercritical CO_2 ($SCCO_2$), and dry-cleaning

processes offer more environmentally sustainable options. Aqueous cleaning solutions, primarily composed of water, are non-toxic and abundant, and their detergents are typically formulated with less hazardous additives. CO_2-based methods utilize carbon dioxide, which is non-flammable, non-toxic, recyclable, and relatively inexpensive. Dry-cleaning techniques such as cryogenic aerosol, plasma, UV-ozone, and laser cleaning minimize environmental liabilities and reduce the risk of material obsolescence, as they rely on cleaning media that are not heavily regulated and generate minimal waste. However, abrasive blasting, while also a dry-cleaning method, must be carefully managed to control exposure to abrasive particles and dislodged contaminants.

Hazardous Waste Stream Generation: In addition to energy consumption and chemical usage, precision cleaning processes must also address the environmental impacts associated with hazardous waste generation. All cleaning methods including dry-cleaning techniques produce waste streams that require appropriate handling and management based on the toxicity, flammability, volatility (particularly the release of VOCs), and recyclability of the cleaning media involved. To mitigate these risks, strict engineering controls and safety protocols must be implemented to ensure the safe use of cleaning agents and the proper disposal of waste materials.

Solvent and aqueous cleaning processes typically generate larger volumes of waste compared to other cleaning methods. Among these, aqueous cleaning often produces the highest waste output due to the multiple stages involved, such as pre-washing, rinsing, and drying. However, innovations such as vacuum cyclic nucleation have been developed to reduce the volume of aqueous solutions required during the cleaning cycle. Additionally, integrating wastewater treatment systems into aqueous cleaning operations can help manage hazardous waste streams more effectively and reduce overall disposal costs.

Although solvent cleaning generally produces less waste volume than aqueous cleaning, it involves the use of liquid media that are often more toxic, more flammable, and more prone to VOC emissions. These characteristics increase the environmental and regulatory risks associated with solvent waste, often resulting in higher disposal costs and stricter compliance requirements. To address these challenges, solvent cleaning systems typically incorporate solvent recovery and recycling units to minimize hazardous waste output and improve sustainability.

Alternative cleaning methods, such as CO_2-based and dry-cleaning processes including laser cleaning, plasma cleaning, and UV-ozone cleaning offer significant environmental and cost advantages by generating minimal waste. The waste streams from these processes are primarily composed of dislodged contaminants, decomposition by-products, and, in some cases, trace amounts of co-solvents. These methods reduce the need for hazardous chemicals and simplify waste management, making them attractive options for environmentally conscious precision cleaning applications.

Table 11. Cleaning Processes and Mechanisms for Surface Decontamination

Cleaning Process	Cleaning Mechanism		Ability to clean materials with complex geometry
	Chemical effect: contaminant dissolution	**Physical Effect: insoluble particulate removal**	
Solvent Cleaning *Open-top vapor degreasing* *Vacuum degreasing* *Vacuum cyclic nucleation*	It utilizes chemical solvents to dissolve contamination such as fluorinated greases and oil, hydrocarbons, and other nonpolar soils.	Cleaning units can be equipped with agitation, ultrasonic system, and fluid flow capability to remove insoluble adherent particulates.	Solvents and vapors can penetrate through internal parts and holes
Aqueous Cleaning *Aqueous detergents* *Vacuum cyclic nucleation*	It uses aqueous detergents, caustic, and acidic solution to remove ionic and polar contaminants. Cleaning solution can be formulated to remove nonpolar soils.	Cleaning units can be equipped with agitation, ultrasonic system, and fluid flow capability to remove insoluble adherent particulates.	Cleaning medium can penetrate through internal parts and holes, but drying complex structures can be challenging
Supercritical Fluid Cleaning	It uses supercritical fluids to dissolve soils. $SCCO_2$ is good at dissolving nonpolar compounds. Co-solvents can be added to remove ionic and polar soils.	Cleaning units can be equipped with agitation, ultrasonic system, and fluid flow capability to remove insoluble adherent particulates.	Supercritical fluids have excellent viscosity, surface tension and wetting property to penetrate through deep holes and pores.
Liquid CO_2 cleaning	It uses LCO_2 for dissolving nonpolar compounds. Co-solvents can be added to remove ionic and polar soils.	Cleaning units can be equipped with agitation, ultrasonic system, and fluid flow capability to remove insoluble adherent particulates.	LCO_2 Less penetrating power than $SCCO_2$, but it can penetrate through deep holes and pores.
Sonic cleaning	It employs a wide range of cleaning medium including organic solvents, aqueous detergents, supercritical fluid to dissolve contaminants.	It utilizes acoustic energy to remove contaminants and unwanted deposits from surfaces via acoustic streaming and cavitation	Cleaning medium can penetrate through internal parts and holes; but drying aqueous solutions can be challenging
Cryogenic aerosol cleaning *Ar/N_2 aerosol* *CO_2 snow* *CO_2 pellet*	CO_2 snow and pellet dissolve nonpolar compounds. CO_2 snow spray chemistry can be modified by adding co-solvents to dissolve contaminants that are insoluble to CO_2.	It dislodges adherent particles through aerodynamic drag force, mechanical impact and energy transfer between the cryogenic particles and surface contaminant.	It is not suitable for cleaning hard-to-reach surfaces such as holes and pores.
Abrasive blasting		It utilizes high velocity stream of abrasive particles projected into the surface to remove contaminants.	It is not suitable for cleaning hard-to-reach surfaces such as holes and pores.
Laser Cleaning		It uses laser energy to remove to thermally ablate and sublimate contaminations.	Internal parts can be cleaned if it's accessible by laser.
Plasma Cleaning	It utilizes plasma gas that can be formulated to induce chemical reaction such as oxidation and reduction of contaminants.	It employs reactive species from plasma to interact with the surface to initiate ablation, sputtering, and thermal evaporation of soils.	Plasma can penetrate fine pores.
Ultraviolet-ozone cleaning	It employs UV-assisted photosensitized oxidation reactions to break down organic molecules into volatile products.	It is not used for removal of gross contamination. Surfaces are precleaned to remove particulates.	UV has limited penetration depth and is not very effective for cleaning fine pores and deep holes.

Table 12. Environmental, Regulatory, and Health Risks of Wet Cleaning Processes

Cleaning Processes	Environmental risk	Health and Safety Risk	Energy Expenditures	Hazardous Waste Generation	Recyclability of Cleaning Medium
Solvent cleaning: *Open-top vapor degreasing*	Solvents have high risk for VOCs, ODP, GWP, and ecological impacts.	Most of the solvents are highly regulated and subject to exposure limit. It increases risks for fire and chemical hazard.	Heat; cooling system; fluid pump; ultrasonics	Generates significant amount of waste. Solvents can be recycled to reduce waste.	Solvents can be recycled using simple distillation system.
Solvent cleaning: *Vacuum degreasing*	It presents similar risk as open-top vapor degreasing, but fully enclosed system minimizes environmental release of vapors.	It presents similar risk as open-top vapor degreasing, but fully enclosed system minimizes health and safety risks.	Heat; cooling system; fluid pump; ultrasonics, vacuum pump	Compared to open-top vapor degreaser, it generates less waste and offers a more efficient and higher rate for solvent regeneration	Solvents can be recycled using simple distillation system.
Aqueous Cleaning: *Aqueous detergents*	Detergents, co-solvents, and additives are generally less toxic than organic solvents. Caustic and acidic solutions require proper handling.	Detergents, co-solvents, and additives are generally less toxic than organic solvents. Caustic and acidic solutions require proper handling.	Heat for cleaning, rinsing, and drying; fluid pumps, ultrasonics for cleaning and rinsing, moving mechanisms	Generates substantially more waste than vapor degreasing. However, water can be treated to reduce hazardous waste.	Detergents, co-solvents, and additives are generally not recovered. Wastewater are treated prior to disposal.
Aqueous Cleaning: *Vacuum cyclic nucleation*	Fully enclosed system reduces environmental risks. VCN does not require large amount of cleaning medium.	Detergents are relatively less toxic than organic solvents except for caustic and acidic solutions. Full enclosure reduces risk for chemical exposure	Heat, pumps, vacuum pump, sonication, drying	It generates less waste compared to conventional aqueous cleaning.	Detergents, co-solvents, and additives are generally not recovered. Wastewater are treated prior to disposal. Organic solvents can be recycled.
Supercritical Fluid Cleaning	CO_2 is abundant, relatively inexpensive, nonflammable, environmentally friendly, nontoxic, and recyclable.	CO_2 presents asphyxiation hazards. Co-solvents and high operating pressures present safety risks.	Heat; pumps; heat exchanger; Compression and decompression of CO_2, sonication, and agitation	Waste stream primarily consists of contaminants and co-solvents which can be recycled.	CO_2 is recyclable and can be regenerated using a simple distillation process
Liquid CO_2 cleaning	CO_2 is abundant, relatively inexpensive, nonflammable, environmentally friendly, nontoxic, and recyclable.	CO_2 presents asphyxiation hazards. Co-solvents and high operating pressures present safety risks.	Heat, pump, sonication, and agitation, compression and decompression of CO_2 but operated at lower pressure than $SCCO_2$	Waste stream primarily consists of contaminants and co-solvents which can be recycled.	CO_2 is recyclable and can be regenerated using a simple distillation process
Sonic cleaning	Environmental risks depend on the cleaning medium.	Risk depends on the cleaning medium and process. It presents noise hazard.	Depends on the cleaning process	Depends on the cleaning medium	Recycling depends on the cleaning medium.

Table 13. Environmental, Regulatory, and Health Risks of Dry Cleaning Processes

Cleaning Processes	Environmental Risk	Health and Safety Risk	Energy Expenditures	Hazardous Waste Generation	Recyclability of Cleaning Medium
Cryogenic aerosol cleaning: *Ar/N_2 aerosol*	Ar and N_2 are environmentally friendly and non-toxic.	It can be an asphyxiation hazard. There's risk of exposure to dislodged contaminants if not properly contained	Pump; cryogenic heat exchanger; moving mechanism (conveyor);	Waste primarily consists of contaminants which can be trapped in HEPA filter	
Cryogenic aerosol cleaning: *CO_2 snow*	CO_2 is abundant, relatively inexpensive, nonflammable, environmentally friendly, nontoxic, and recyclable	CO_2 presents asphyxiation hazards. There's risk of exposure to dislodged contaminants if not properly contained.	Pump; cooling; moving mechanism (conveyor);	Waste primarily consists of contaminants and co-solvents	CO_2 is recyclable and can be regenerated using a simple distillation process
Cryogenic aerosol cleaning *CO_2 pellet*	CO_2 is abundant, relatively inexpensive, nonflammable, environmentally friendly, nontoxic, and recyclable	CO_2 presents asphyxiation hazards. There's risk of exposure to dislodged contaminants if not properly contained.	Pump; cooling; moving mechanism (conveyor); compressor	Waste primarily consists of contaminants which can be trapped in HEPA filter	CO_2 is recyclable and can be regenerated using a simple distillation process
Abrasive blasting	It presents risks for air pollution and environmental release of abrasive particles and dislodged contaminants.	It presents risks for exposure to respirable toxic dust which can cause silicosis and physical injury.	Pump; vacuum/exhaust fan	Waste consists of abrasive particles with contamination. Particles can be reused and recycled.	Blast cabinet/room enable recycling of abrasive particles.
Laser Cleaning	It presents risks for environmental release of dislodged contaminants.	It presents risks for exposure to laser radiation and exposure to hazardous fumes from dislodged contaminants.	Laser, cooling, robotic control, vacuum/exhaust fan to sweep away dislodged contaminants	Waste primarily consists of contaminants and co-solvents.	Dry laser cleaning does not use solvents for cleaning. Co-solvents can be recycled.
Plasma Cleaning	It presents risks for exposure to hazardous fumes from decomposition products of plasma-induced reactions.	It presents risks for exposure to radiation and hazardous fumes.	Plasma generation and maintaining vacuum are energy intensive processes; pump; maintaining vacuum pressure	Waste primarily consists of contaminants and decomposition products of plasma-induced reactions.	
Ultraviolet-ozone cleaning	Presents risks for exposure to hazardous fumes from decomposition products.	It presents risks for exposure to UV radiation, ozone, intense light, and hazardous fumes.	UV and ozone generator; moving mechanisms; fluid pump	Waste primarily consists of contaminants and decomposition products.	

Table 14. Scalability and Facility Requirements of Cleaning Processes.

Cleaning Processes	Facility Requirement	Scalability*
Solvent cleaning: *Open-top vapor degreasing* *Vacuum degreasing*	It requires adequate ventilation, clean room environment, and solvent recycling system. Facility must adhere to safety and environmental regulations such as handling and storage of chemicals, personnel exposure limits, hazardous waste management system, and fire safety.	It can be scaled up to clean large components. Scaling increases risk for fire and chemical hazards.
Aqueous Cleaning: *Aqueous detergents*	It requires large footprint for cleaning baths, rinsing baths, drying chambers, and waste stream storage. It requires adequate ventilation, clean room environment, and hazardous waste management system. Acidic and caustic baths should follow safety requirements for handling and storage of corrosive chemicals.	The size of the cleaning bath, rinsing bath, and drying chambers must be able to accommodate the size of the material to be cleaned. Scaling increases energy expenditures and waste stream generation. Scaling also requires bigger facility.
Aqueous Cleaning: *Vacuum cyclic nucleation*	It requires less footprint than cleaning with aqueous detergents. Facilities should have hazardous waste management and clean room environment.	Can be scaled to clean large structures, but may not be practical
Supercritical Fluid and LCO_2 Cleaning	Facilities need adequate ventilation, O_2 monitoring system to prevent asphyxiation, CO_2 recycling system.	Scaling up high-pressure systems can be costly.
Sonic cleaning	Facility requirements depend on the cleaning process (solvent, aqueous, $SCCO_2$, or LCO_2 cleaning, etc.)	Scalability depends on the cleaning process (solvent, aqueous, $SCCO_2$, or LCO_2 cleaning, etc.)
Cryogenic aerosol cleaning: *Ar/N_2 aerosol* *CO_2 snow* *CO_2 pellet*	Facility must have adequate ventilation. The process requires air flow management to create a dry environment. Cleaning unit must be able to control surface electrostatic discharge.	It is scalable. Scaling should be equipped with moisture control and electrostatic charge control.
Abrasive blasting	It can be performed in an open space, blast cabinet or blast room. Blast cabinet/room may incorporate a recycling process to reuse abrasive particles.	It is scalable. It is used to clean large scale structures such as bridges and buildings.
Laser Cleaning	It can also be performed under air or inert gas environment. It is performed in a fully enclosed area and interlocking doors to prevent accidental exposure to laser radiation. It requires ventilation/exhaust system to sweep away dislodged contaminants.	It is scalable.
Plasma Cleaning	Facility must have adequate ventilation. It requires vacuum chamber. It also requires process control and monitoring systems	It is highly scalable. Scaling will require large vacuum chambers and must address the challenges associated with uniform distribution of plasma in the chamber.
Ultraviolet-ozone cleaning	Facility must have adequate ventilation. Cleaning unit must be fully enclosed and integrate safety interlocks to prevent UV and ozone exposure.	It is scalable, but cleaning large structures may be time-consuming. It is not suitable for removing gross contamination. Materials may need to be pre-cleaned prior to UV-ozone treatment.

*: The flexibility of the process to clean parts with complex geometries and remove a wide range of contamination is provided in Table 11.

7.3.1.11.4 Safety and Health Risks

Precision cleaning processes present a range of safety and health risks that must be carefully managed to protect personnel and maintain regulatory compliance. These risks include electrical, radiation, physical, and chemical hazards, as shown in Table 12 and Table 13. The specialized equipment used in cleaning operations can expose workers to electrical hazards, particularly during maintenance or improper operation. Radiation exposure is a concern in processes such as plasma, ultraviolet (UV)-ozone, and laser cleaning, which involve high-energy emissions. Physical hazards are also present; for example, the high operating pressures associated with supercritical and liquid carbon dioxide ($SCCO_2$ and LCO_2) systems, as well as the high-velocity particle streams used in abrasive blasting, can result in physical injuries. Sonic cleaning may generate high-frequency noise levels that pose auditory risks.

Additionally, dry-cleaning methods including abrasive blasting, cryogenic aerosol, laser, plasma, and UV-ozone cleaning can dislodge contaminants and produce airborne particulates or fumes, creating inhalation hazards for operators. The improper handling, storage, or use of flammable solvents further increases the risk of fire and explosion.

Chemical cleaning media also pose significant health and safety concerns due to their toxicological properties. Exposure to chemical solvents may result in acute toxicity, carcinogenicity, reproductive toxicity, respiratory irritation, eye damage, or skin sensitization. These hazards necessitate a thorough understanding of the toxicological profiles of the substances used. Many solvents are subject to strict regulatory controls and occupational exposure limits, which must be considered when developing workplace safety protocols. To ensure operator safety, it is essential to understand the specific hazards associated with each cleaning process and implement appropriate risk mitigation strategies. These include the use of PPE, comprehensive and up-to-date personnel training, regular equipment maintenance, and the incorporation of automation to reduce direct human exposure. Proper ventilation systems must be installed to manage airborne contaminants, and engineering controls should be established to contain and minimize exposure risks. Additionally, robust safety protocols and continuous safety monitoring systems are critical components of a comprehensive health and safety management plan for precision cleaning operations.

7.3.1.11.5 Facility Requirements

Precision cleaning operations require carefully controlled environments and purpose-built facilities to ensure compliance with safety and environmental regulations, as well as to achieve the high levels of cleanliness demanded by many applications. Cleanroom environments are often necessary to prevent recontamination and to maintain particulate control. The construction materials used for both the cleaning units and the surrounding facilities must be compatible with the cleaning media employed. For example, components exposed to acidic or caustic aqueous solutions must be resistant to corrosion to ensure long-term durability and operational safety. Additionally, facilities must be equipped with adequate ventilation systems to safely manage flammable or toxic solvent vapors, and they must be designed to accommodate the safe handling and storage of hazardous chemicals.

All cleaning processes generate waste streams, although the volume and composition vary depending on the method used. To address the associated environmental, health, and safety risks, facilities must incorporate robust hazardous waste management and disposal systems. In some

cases, solvent recycling systems are integrated into the process to reduce waste generation and improve sustainability.

Effective process control and monitoring systems are essential for maintaining optimal operational parameters across all cleaning methods. Facilities must also be equipped with safety monitoring systems tailored to the specific hazards of each process. For instance, supercritical and liquid CO_2 cleaning systems require oxygen monitoring to detect potential displacement of breathable air. UV-ozone cleaning chambers must include safety interlocks to prevent accidental exposure to ultraviolet radiation and ozone gas. A summary of facility requirements for various cleaning processes is provided in Table 14.

7.3.1.11.6 Scalability

The scalability of precision cleaning processes involves the development of flexible and efficient systems capable of accommodating diverse cleaning requirements and fluctuating operational demands while maintaining consistent performance and cleanliness standards. A scalable cleaning process must be adaptable to varying levels of cleanliness, different sizes and geometries of components, and a wide range of contamination types. For instance, substrates with heavy contamination may require surface pretreatment to achieve the desired cleanliness level. Additionally, scalability must account for the ability to clean components with complex structural features such as deep pores, blind holes, and internal cavities (Table 11). The process should also be capable of removing various contaminant types, including ionic, polar, nonpolar, and particulate matter (Table 11). The scalability characteristics of different cleaning processes are summarized in Table 14.

Several factors influence the scalability of precision cleaning systems, including technical challenges, safety considerations, environmental regulations, waste and resource management, energy consumption, disposal costs, facility requirements, and the integration of automation and digital monitoring technologies. Scaling up a process often introduces technical complexities, particularly when adapting high-pressure systems or vacuum chambers, which require careful design to ensure compatibility with existing infrastructure and compliance with regulatory standards. Facility modifications may be necessary to support increased throughput, including upgrades to cleanroom environments to accommodate larger volumes of components.

Resource management is another critical consideration in scaling operations. Increased throughput demands greater quantities of consumables, labor, and energy. The availability and sustainability of chemical solvents must be evaluated, as scaling up typically results in higher solvent consumption. Additionally, the financial implications of increased energy use, waste generation, regulatory compliance, and facility expansion must be carefully assessed. Implementing robotic automation and real-time monitoring systems can significantly enhance scalability by improving process consistency, reducing human error, and enabling continuous performance tracking. These technologies support the efficient and reliable expansion of precision cleaning operations while maintaining high standards of safety, environmental compliance, and cleaning effectiveness.

7.4 Task 2: Novel Precision Cleaning Technologies Proof-of-Concept Testing

The evaluation of novel cleaning technologies is essential for advancing precision cleaning processes while addressing environmental, operational, and economic challenges. Traditional solvent-based cleaning methods often involve hazardous chemicals that pose risks to personnel

safety, generate regulated waste streams, and incur significant disposal costs. By exploring solvent-free approaches or optimizing solvent/detergent formulations for specific use cases, organizations can reduce chemical dependency, improve sustainability, and comply with increasingly stringent environmental regulations. Additionally, technologies that extend solvent life through filtration or regeneration minimize resource consumption and operational downtime, while reducing overall lifecycle costs. Beyond environmental and cost benefits, these innovations can enhance cleaning efficiency and precision, enabling tailored solutions for complex contamination scenarios such as aerospace components or high-performance systems. Novel methods—such as magnetic or electrostatic techniques—offer opportunities to improve contaminant removal without increasing process complexity, supporting long-term goals of reliability, safety, and cost-effectiveness in mission-critical applications.

7.4.1 Magnetically Optimized Fluids (MOF)

Magnetic fields have been demonstrated to alter the physicochemical properties of solvents [128, 129, 130, 131, 132, 133, 134]. Studies have shown that magnetic fields affect the properties of water such as pH, specific heat, boiling point, and conductivity [128, 133, 131, 129]. Researchers have also found that treating water or aqueous solutions with a magnetic field can cause measurable changes in optical properties, conductivity, dielectric constant, viscosity, absorption spectrum, chemical reactions, surface tension, adsorption/condensation characteristics, and electrochemical effects [129]. These changes are attributed to the influence of the Lorentz force on intermolecular interactions [129]. Magnetization strengthens intermolecular hydrogen bonding in water, increases activation energy, and influences the formation and re-orientation of hydrogen bonds, leading to slower rotational motion and stronger inter-cluster hydrogen bonds [128, 131]. This results in architectural changes in water, increasing the size and proportion of molecule clusters and forming networks of clusters [131].

The impact of the Lorentz force on intermolecular interactions and the resulting changes in the physicochemical properties of liquids have garnered scientific interests. A publication reviewed the applications of magnetized solvents across various fields, including chemistry, agriculture, oil extraction, medicine, and the automobile industry [135]. This paper also suggests that magnetic fields affect both polar and non-polar solvents [135]. A study using molecular dynamics simulations examined the effect of an external constant magnetic field in the Z-direction on common solvents like water, acetone, acetonitrile, toluene, and n-hexane [130]. The magnetic field reduced solvent mobility, enhancing solvent-solute reactions, and decreased solvent diffusivity and volume while increasing hydrogen bond strength through enhanced electrostatic and van der Waals interactions [130].

The effects of external magnetic fields on solvent properties for cleaning applications were studied to specifically examine how magnetic fields influence UV-Vis absorption, vapor pressure, and cleaning performance by leveraging changes in physicochemical properties when solvents are exposed to magnetic fields. Four solvents were tested: DI water, isopropyl alcohol (IPA), 50% (w/w) IPA in DI water, and BestSolv® Sierra. DI water was specifically evaluated due to its dipole characteristics and hydrogen bonds, which are influenced by magnetic fields. Magnetization alters the macroscopic and physicochemical properties of water through atomic polarization and changes in dipole moments [131]. Magnetization of water is also widely reported in the literature. In addition, water is the major component in aqueous detergents. IPA is a versatile solvent that is widely used for cleaning due to its effectiveness in dissolving oils, greases, and other contaminants. Its high vapor pressure allows for rapid evaporation, leaving no

residue on the surface and reducing drying time. IPA is compatible with various materials, including metals, polymers, and plastics. Its low viscosity makes it easy to spread and penetrate fine pores. As a highly polar organic solvent due to the hydroxyl (OH) group, IPA can form hydrogen bonds with water, making it highly soluble in water (**Error! Reference source not found.**) [136]. This strong polarity gives IPA excellent solubility for a broad range of contaminants.

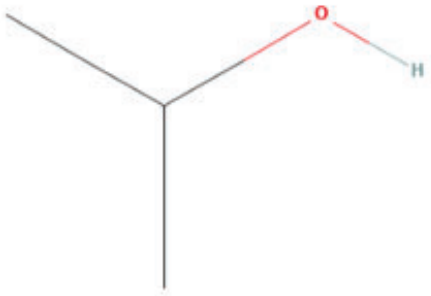


Figure 26. Molecular structure of IPA showing the hydroxyl (OH) group [136].

BestSolv Sierra is a non-flammable engineered fluid formulated as a drop-in alternative fluid for 3M Novec 7100 [137] . It is a colorless liquid with boiling point of 56.2 ºC and vapor pressure of 31kPa at 25 ºC [138]. The solvent is designed for industrial applications including precision cleaning and vapor degreasing [137]. It is a high-purity, neat HFE fluid with proprietary chemical composition that is not considered a PFAS [137, 138]. HFEs are organic solvents designed to replace CFCs, HCFCs, and PFCs due to their relatively low global warming potential [139]. HFEs have been commercially developed for use as cleaning solvents, including Novec™ HFE-7000, HFE-7100, HFE-7200, and HFE-7500 [139].

7.4.1.1 Experimental Setup

Magnetized Solvents

Fluids were magnetized by using the experimental set-up shown in Figure 27 which consisted of two Alnico U-channel magnets (McMaster-Carr) that were tightly taped together and clamped to a ring stand. Each magnet measured 6 inches in length, 1 inch in width, and 5/8 inch in thickness. The hollow center of the taped magnets accommodated a 5-mL glass pipette. The magnetic field strength around the hollow center was measured (Figure 27). Solvents were drawn into the pipette using a pipette filler or bulb and exposed to the magnet for 10 minutes. After this period, the solvents were collected for testing.

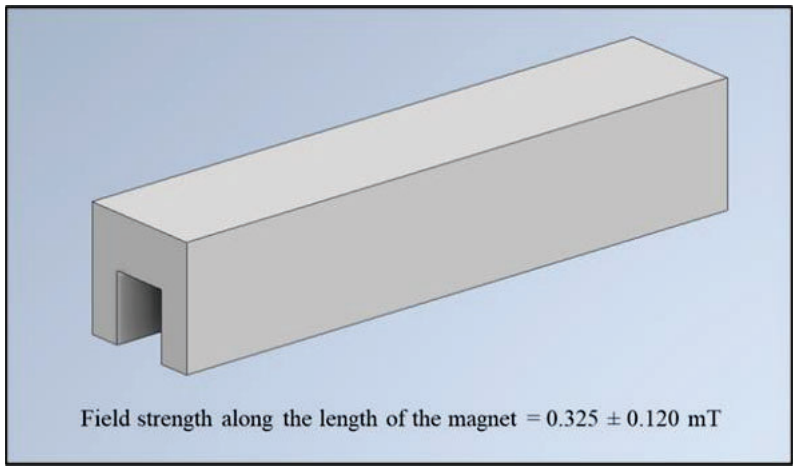


Figure 27. Field strength along the length of the alnico U-channel magnet.

Non-Magnetized Solvents

The same procedure was followed to test the non-magnetized solvent. However, this time, the solvents were not exposed to the magnetic field. Solvents were drawn into a 5-mL glass pipette using a pipette filler or bulb. The solvents were allowed to sit in the pipette for 10-minutes prior to sample collection.

UV-Vis Absorption

The ultraviolet-visible (UV-Vis) absorption spectra of both magnetized and non-magnetized solvents were measured using a NanoDrop spectrophotometer (Thermo Scientific). A 2-µL solvent was pipetted into the sample holder, and a UV-Vis spectral scan was performed, measuring the absorbance from 190 nm to 850 nm at 0.5 nm intervals. The absorbance of both magnetized and non-magnetized solvents was measured relative to a blank solution, which was the non-magnetized solvent. Measurements were conducted under ambient conditions, with each measurement performed five times. The variation of data relative to the mean value was calculated using 1 standard deviation (1σ).

Vapor Pressure

Vapor pressure of both magnetized and non-magnetized solvents was measured using Minivap VP Vision by Grabner Instruments (Ametek) with up-to-date calibration. The instrument measures vapor pressures up to 150 kPa from 0 °C to 120 °C. The performance of the instrument was verified using high purity n-pentane. Vapor pressure measurements were performed using ASTM D6378 [140]. The vapor pressure of solvents was measured at 25 °C with a vapor-liquid (V/L) ratio of 4. The instrument was rinsed three times with the solvent before starting the measurements. Vapor pressure measurements were performed at least three times. The variation of data relative to the mean value was calculated using 1 standard deviation (1σ).

Cleaning Performance

The cleaning performance of both magnetized and non-magnetized solvents was evaluated by weighing contaminated coupons before and after treatment. The coupons were contaminated with a mixed contaminant stream which is a mixture of Krytox 240 AC, Braycote 601, dioctyl sebacate, Brayco 882, and light mineral oil in EnSolv Fluoro-IC. The mixed contaminant stream was prepared by sonicating the mixture for 45 minutes at 60 °C. Twenty-four T7075 Aluminum

coupons were prepared by washing in a soap solution, rinsing with DI water, and drying in an oven for a day. The coupons were allowed to cool in a desiccator. After cooling, the mixed contaminant stream was applied on the coupon using a sure-shot spray can. The contaminated coupons were aged in an oven for 3 days, cooled in a desiccator, and evaluated gravimetrically. The mass of the coupons was measured before and after solvent treatment. The amount of contaminants removed by the solvent was calculated using Equation 4, where m_b is the mass of contaminated coupon before solvent treatment, m_a is the mass of contaminated coupon after solvent treatment, and m_c is the mass of contaminants applied to the coupon.

Equation 4. $$\textbf{\textit{Amount of contaminant removed}} = \frac{m_b - m_a}{m_c} * 100\%$$

Measurements were performed in triplicate under ambient conditions. The variation of data relative to the mean value was calculated using 1 standard deviation (1σ).

7.4.1.2 Results

UV-Vis Absorption

The absorbance of the solvents in the UV-Vis spectrum is shown in Figure 28-Figure 31, which display the average of the five measurements performed for each solvent. Error bars were calculated as ±1σ although they are not shown in the Figures as they make the plots appear cluttered. The error bars overlapped for all test conditions indicating absorbance between the magnetized and non-magnetized solvents was comparable.

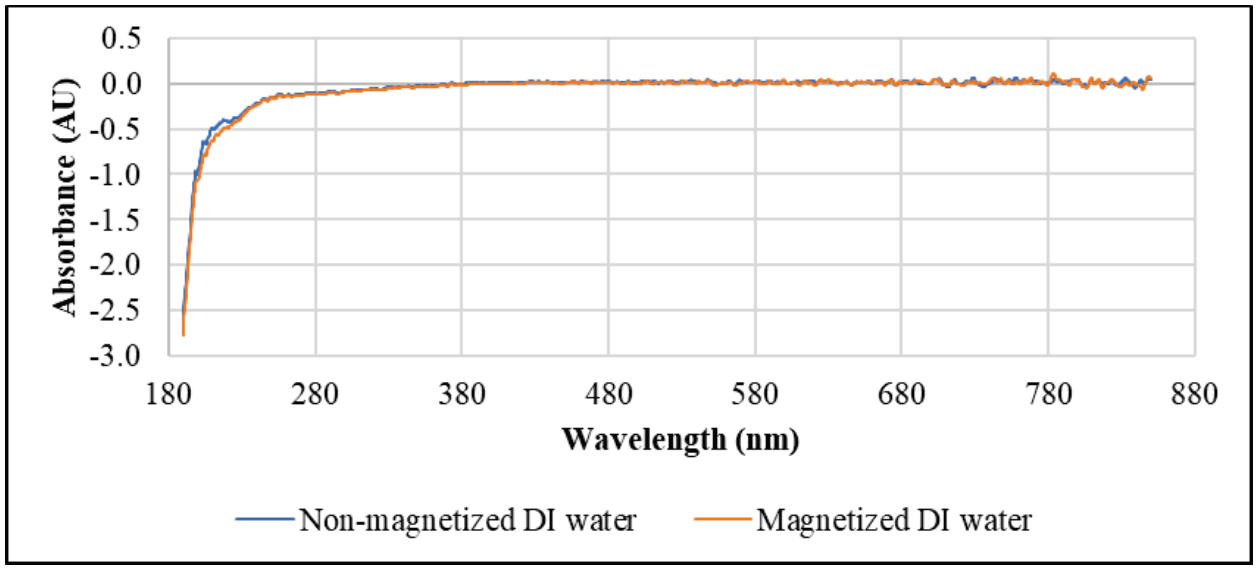


Figure 28. UV-Vis absorption spectrum of non-magnetized and magnetized DI water.

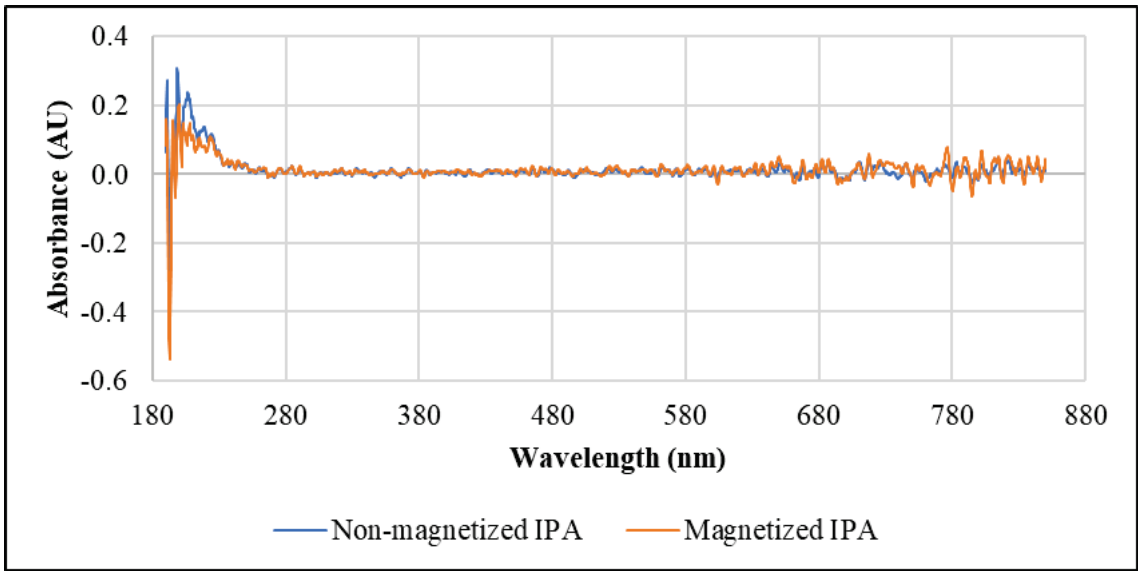


Figure 29. UV-Vis absorption spectrum of non-magnetized and magnetized IPA.

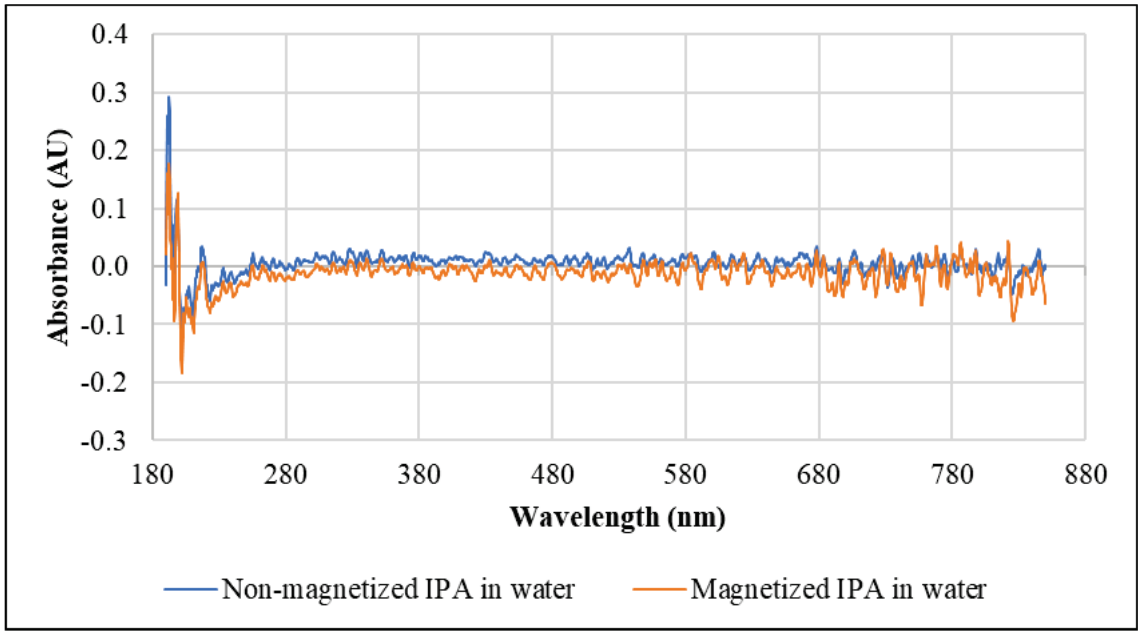


Figure 30. UV-Vis absorption spectrum of non-magnetized and magnetized 50% (w/w) IPA in water.

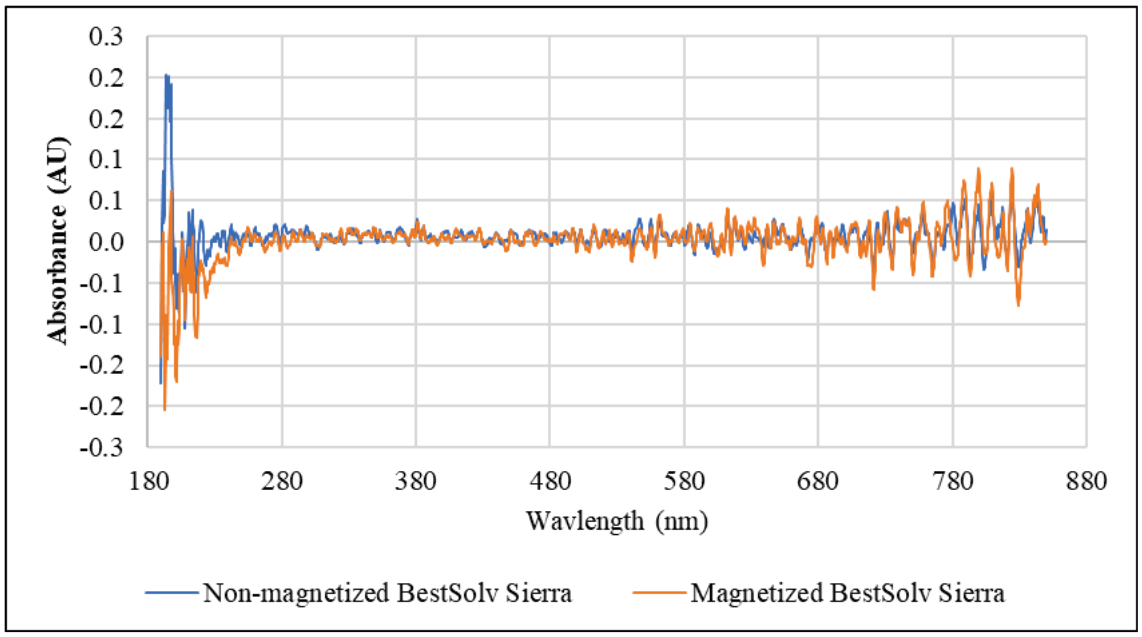


Figure 31. UV-Vis absorption spectrum of non-magnetized and magnetized BestSolv Sierra.

Vapor Pressure

The vapor pressure of both magnetized and non-magnetized solvents is shown in Figure 32 and Table 15. Statistical analysis was performed using Analysis of Variance (ANOVA) followed by pairwise comparisons using the Tukey method to compare the performance of the solvents at a 95% confidence level. Results showed that BestSolv® Sierra has the highest vapor pressure among the four solvents evaluated in this study. The addition of water resulted in a statistically significant increase in the vapor pressure of IPA at 25°C. IPA forms an azeotrope mixture with water. The results also showed the vapor pressure of magnetized solvents is slightly higher than the non-magnetized solvents under the testing conditions.

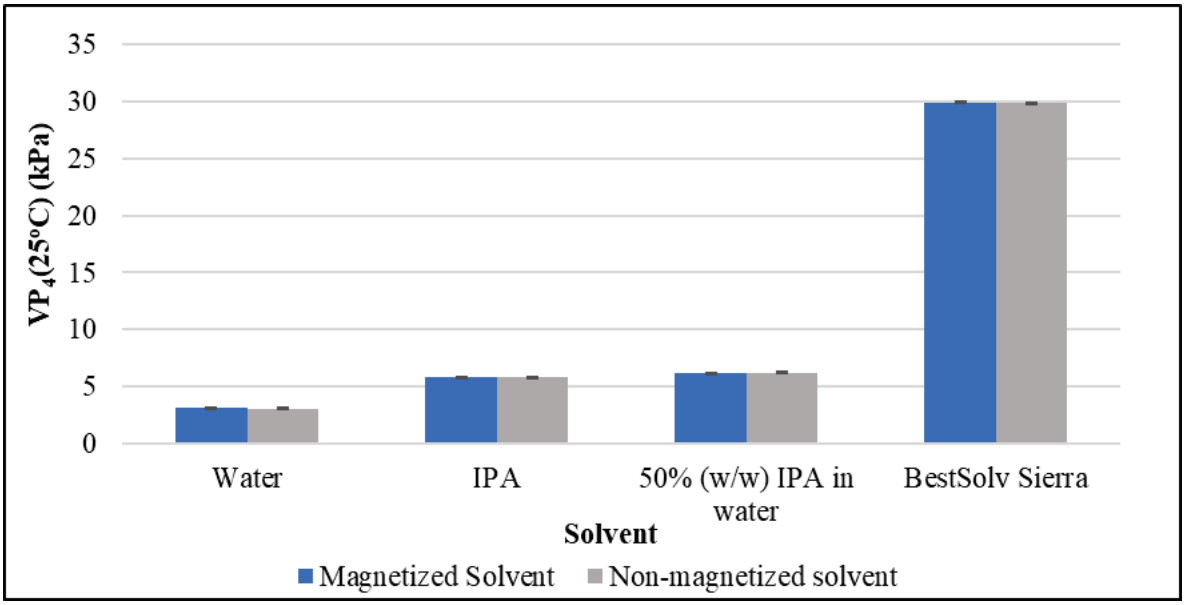


Figure 32. Vapor pressure of magnetized and non-magnetized solvents at 25 °C. Error bars represent ±1σ.

Table 15. VP and Cleaning Performance of Magnetized and Non-Magnetized Solvents

Solvent	Amount of Contaminant Removed (% w/w)	Vapor Pressure at 25 °C (kPa)
Magnetized water	38.75 ± 0.32	3.06 ± 0.04
Non-magnetized water	34.32 ± 6.37	3.05 ± 0.03
Magnetized IPA	83.28 ± 7.80	5.82 ± 0.02
Non-magnetized IPA	88.08 ± 7.42	5.80 ± 0.01
Magnetized IPA (50% w/w in water)	58.51 ± 12.96	6.16 ± 0.04
Non-magnetized IPA (50% w/w in water)	49.95 ± 10.54	6.16 ± 0.06
Magnetized BestSolv Sierra	63.59 ± 3.36	29.94 ± 0.02
Non-magnetized BestSolv Sierra	67.89 ± 0.47	29.85 ± 0.08

Cleaning Performance

The cleaning performance of both the magnetized and non-magnetized solvents was evaluated based on their effectiveness in removing Witches' Brew contaminants. The summary of results is shown in Figure 33 and Table 15. Among the four solvents evaluated, IPA was the most effective in removing Witches' Brew from the coupons, and BestSolv® Sierra and 50% (w/w) IPA in water had similar performance. Results indicated that there is no statistically significant difference between the cleaning performance of magnetized and non-magnetized solvents under the testing conditions. Typically, room temperature solvents are not used for cleaning processes and are generally required in larger quantities than those produced in this experiment.

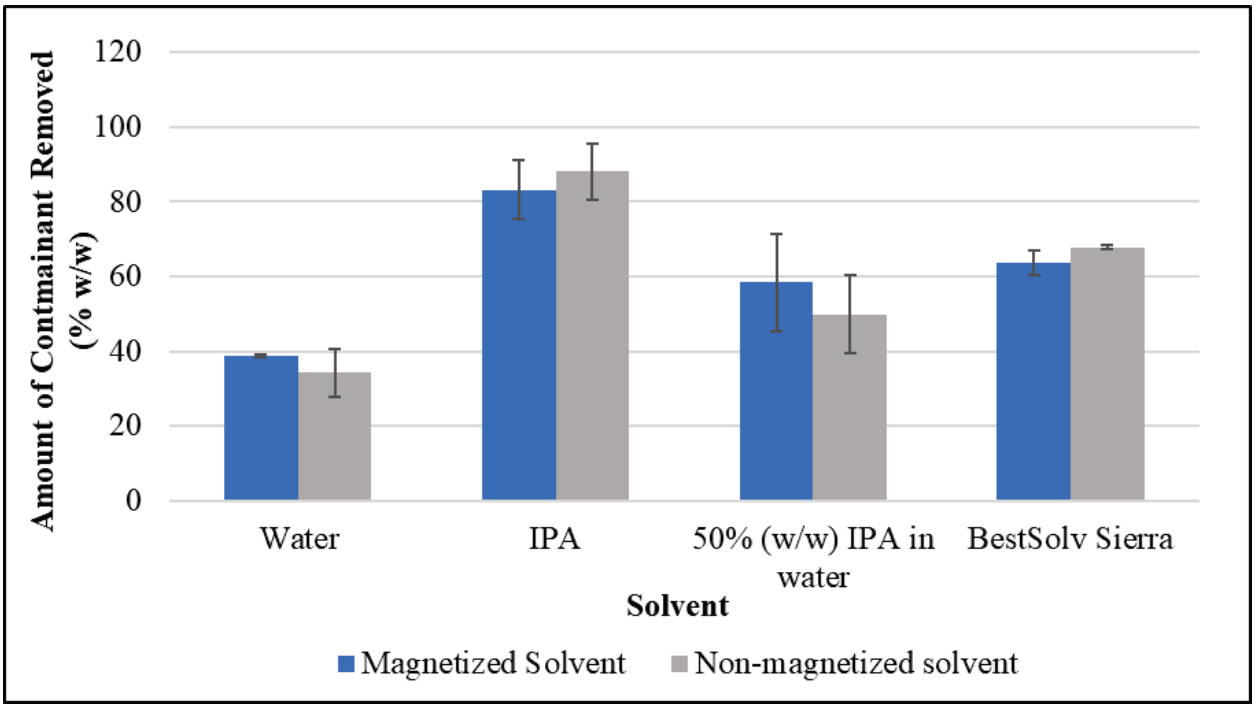


Figure 33. Cleaning performance of magnetized and non-magnetized solvents. Error bars represent ± 1σ.

7.4.1.3 Summary of Proof-of-Concept MOF Testing

The effects of magnetic fields on the properties of four solvents: DI water, isopropyl alcohol (IPA), 50% (w/w) IPA in DI water, and BestSolv® Sierra were evaluated. These solvents are used as cleaning mediums for contaminant removal. Water and IPA are common solvents in precision cleaning, while BestSolv® Sierra is a drop-in alternative fluid candidate for 3M Novec™ HFE-7100. The solvents were evaluated for UV-Vis absorption, vapor pressure, and cleaning performance. Analysis showed that magnetization resulted in a small increase in vapor pressure but did not significantly impact cleaning performance under the testing conditions. Other factors, such as varying the magnetic field strengths, solvent flow rate, and magnet exposure time, were not evaluated in this study.

7.4.2 Induced Charge Active Filtration (ICAF)

Another novel alternative cleaning technology developed and tested for proof-of-concept under this assessment was the concept of Induced Charge Active Filtration (ICAF). The goal with the ICAF device is to actively filter out primarily non-metallic materials (e.g., PTFE/Teflon powder, general foreign object debris) but also potentially non-ferrous metals (e.g., aluminum, titanium, Inconel/nickel-based alloys) and without the traditional use of filters. The removal of traditional in-line filters with non-disruptive technologies offers many potential advantages. Removing particulate contaminants from cleaning fluids is critical for proper cleaning, performance, efficiency, and reuse. The ICAF concept and initial prototype looked at demonstrating particulate removal from cleaning fluids using electric and magnetic fields to separate particles from liquids. This process is similar to an electrostatic precipitator, but in a liquid (deionized water for testing) as opposed to a gas. However, this technology is also different in that it uses the magnetic field to circularly pull the particulates out of solution. Magnetic fields have been used in the past to deflect charge radiation (alpha, beta, and gamma). The first iteration of ICAF was assembled and

screened at NASA MSFC by the contamination control team and conducted initial feasibility of ICAF to determine if non-ferrous powder particles could be pulled using magnetic fields and captured.

7.4.2.1 Modeling of Particulate Separation in Liquids

Traditional gravity-based separation for particulate suspended in liquids is ineffective for particles smaller than 100 µm due to buoyancy and viscous forces. Alternative techniques that utilize external fields, such as magnetophoresis, electrophoresis (EP), and dielectrophoresis (DEP), may offer improved selectivity and efficiency. A preliminary model-based study on separating microparticles suspended in liquids through three mechanisms: magnetophoresis, EP, and DEP, was completed using COMSOL software. The study examined the effects of gravitational, magnetic, and electric-driven (electrophoretic and dielectrophoretic) forces on the separation of microparticles in various liquid media. Particles listed and or evaluated included PTFE (Teflon), alumina (Al_2O_3), titanium, Inconel 718, aluminum, MGS-1 regolith simulant, and LHS-1 regolith simulant. Liquid media included DI water, Novec HFE-7100, and SAE 5 weight oil. Combinations of these were evaluated under various fluid flow, particle size and electric/magnetic field conditions.

Gravity and Drag Effects

For a PTFE sphere with a diameter of 40 µm, the net downward force is 3.95×10^{-10} N, which might suggest that the microparticle should settle quickly, and that gravity should be sufficient to separate the PTFE microparticles. However, viscous drag force (Stokes drag) in water quickly opposes this force, resulting in a very slow terminal velocity that nearly immediately cancels out the expected gravitational pull. Therefore, gravity alone is ineffective for microparticle separation in DI water. Assuming a perfect spherical microparticle and neglecting the viscous drag effect, the general Stokes drag equation can be written as:

Equation 5. $$\boldsymbol{F_{drag} = 3\pi\mu d_{eq}\chi v}$$

Where,

$d_{eq} = Equivalent\ Diameter = \left(\frac{6V}{\pi}\right)^{1/3}$

χ = Dynamic Shape Factor (non-sphericity factor, $\geqq 1$)

The Stoke terminal microparticle velocity becomes:

Equation 6. $$\boldsymbol{v_t = \left(\frac{\Delta\rho\ g\ d_{eq}^2}{18\,\mu\,\chi}\right) = \frac{v_{t,sphere}}{\chi}}$$

Where

ρ_p = particle density (PTFE ≈ 2200 kg/m^3)

ρ_f = fluid density (Water at 25 °C ≈ 997 kg/m^3)

$\Delta\rho = \rho_p - \rho_f$

g = gravity (9.81 m/s)

Magnetophoresis

Fundamentals: The magnetophoretic force depends on the microparticle size and the difference in magnetic susceptibility between the microparticle and the fluid. It is effective only in the

presence of a magnetic field gradient. A key property of the magnet used in magnetophoresis is its Remanent flux density (denoted Br), which is the magnetic flux density that remains in a magnetic material after an external magnetizing field (H) is removed. Table 16 displays the most common commercially available permanent magnets and their corresponding Remanent flux density values.

Table 16. Remanent Flux Density in Materials when H = 0

Material	Typical B_r Range (T)
NdFeB (Neodymium)	1.3-147
SmCo	0.9-1.1
AlNiCo	0.6-1.3
Ferrite	0.2-0.4

The NdFeB (Neodymium), listed in Table 16, with a Remanent value of 1.3-1.4, is the most widely used permanent magnet in industry and is employed in this model-based study. At a given magnetic field gradient, the magnetophoretic force experienced by a microparticle depends on its size and the difference between its magnetic susceptibility and that of the surrounding fluid:

Equation 7. $$\boldsymbol{F_m = \frac{\mu_0 V_p \Delta\chi}{2} \nabla H^2}$$

Where

μ_0 = Vacuum Permeability

V_p = Particle Volume

$\Delta\chi$ = Particle Fluid Susceptibility Difference = $\chi_p - \chi_f$

H = Magnetic Field Strength

Table 17 shows the susceptibility of illustrative materials and their difference with DI water ($\chi_v = -9.05 \times 10^{-6}$). The table also shows the magnetic response of these materials in water. If the difference in magnetic susceptibility between the material and the fluid is negative, the material becomes diamagnetic in the fluid, meaning the microparticles are repelled from the magnet. Conversely, when the difference is positive, the microparticles are attracted toward the magnet.

Table 17. Susceptibility of Illustrative Materials and Their Difference with DI Water ($\chi_v = -9.05x10^{-6}$)

Particle Type	χ (Approximate)	Magnetic Behavior	Δχ
PTFE Powder	$-10.28x10^{-4}$	Diamagnetic	$-1.23x10^{-4}$
Alumina (Al_2O_3) Powder	$-4x10^{-9}$ to $-4x10^{-6}$	Diamagnetic	$-9.05x10^{-6}$/$-5.05x10^{-6}$
Titanium Powder	$+1.8x10^{-4}$	Paramagnetic	$+1.8x10^{-4}$
Inconel 718 Powder	$+2.5x10^{-3}$	Paramagnetic	$+2.5x10^{-3}$
Aluminum Powder	$+2.2x10^{-5}$	Paramagnetic	$-3.1x10^{-5}$
MGS-1 Regolith Simulant	$+10^{-6}$ to 10^{-5}	Paramagnetic	$+10.05x10^{-5}$/$1.9x10^{-5}$
LHS-1 Regolith Simulant	$+10^{-5}$ to 10^{-4}	Paramagnetic	$+1.9x10^{-5}$/10^{-4}

Multiphysics 2D Model: The Multiphysics model is based on the integration of three physics, fluid flow with velocity and pressure of the fluid as the dependent variables, the magnetic field generated by the magnet in the fluid with the vectorial field as the dependent variable, and the tracing of the microparticles that experience the magnetic force illustrated in Equation 7 along with the other concurring forces, the convective and viscous drag forces, the buoyancy and the gravity forces. All the concurring forces are solved for each one of the microparticles in the flow.

The model is solved in transient mode for the microparticle-tracing physics as forces on the microparticle and their position change with time. The fluid flow is solved in stationary mode, as it is assumed that the microparticles are small enough not to affect the flow pattern/velocity. Figure 34 illustrates the outcome profile of a) fluid flow, b) magnetic field, and c) microparticle tracing.

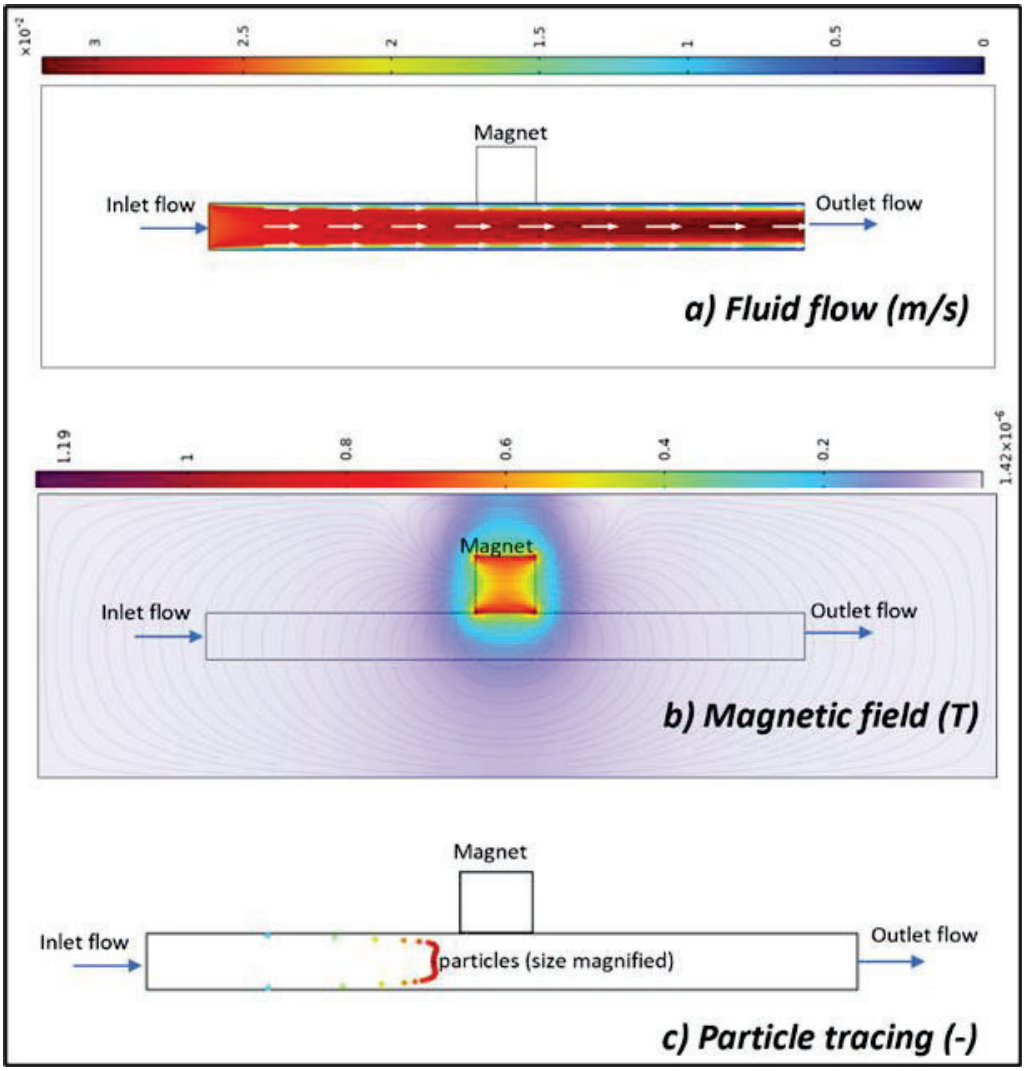


Figure 34. The three physics solved in the magnetophoresis model: a) fluid flow velocity, b) magnetic field, and c) microparticle tracing position.

The multiphysics model's domains include a single flow channel and the magnets along the channel, as shown in Figure 35. The primary domain parameters include the dimensions (width and length) of the flow channel and the magnets, as well as the number and placement or pitch of the magnets. The initial study focused on the effect of one domain parameter (the width of the flow channel), the number of magnet domains in series, and one dependent variable (inlet flow velocity).

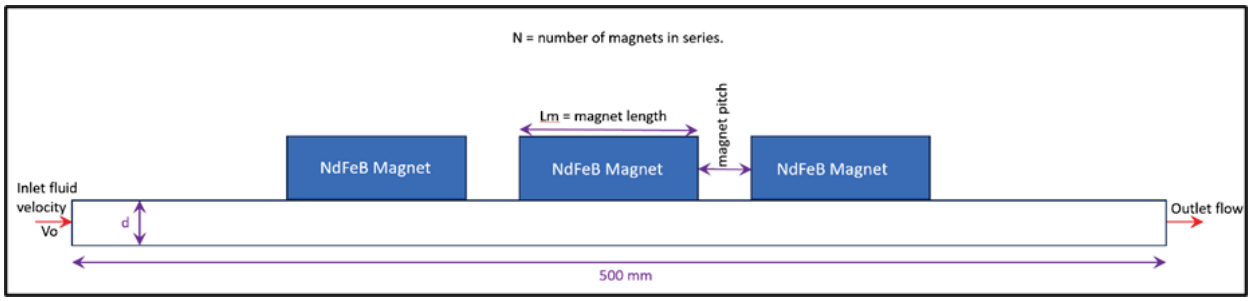


Figure 35. Multiphysics Model's Domains

Selected Multiphysics 2D Model Case: For aluminum microparticles in SAE 5W fluid, with a diameter of 0.04 mm (40 µm) and a flow channel length of 500 mm, a preliminary model-based study (no optimization) was conducted to determine the inlet fluid velocity, the flow channel width, and the number of magnets with specific dimensions needed to remove the microparticles. The study found that an inlet flow velocity of 2.5 x 10^{-4} m/s and four magnets result in complete separation of the microparticles, as shown in Figure 36.

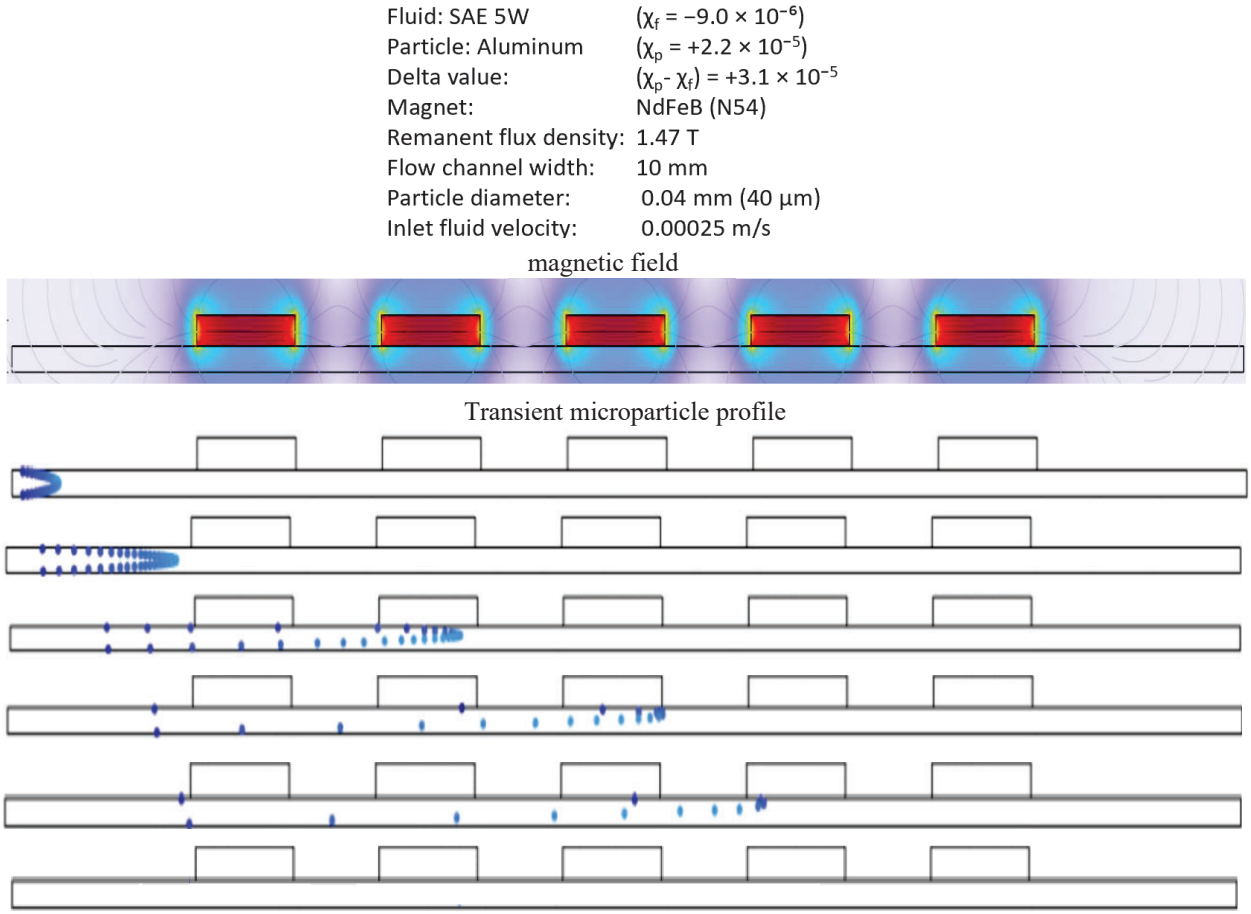


Figure 36. Magnetophoretic separation of 40-µm-diameter aluminum microparticles in SAE 5W fluid with 2.5x10^{-4} m/s inlet fluid flow and four magnets.

As shown in Figure 36, aluminum microparticles with a diameter of 40 µm in SAE 5W fluid are primarily removed through magnetophoresis using four magnets, with a fluid inlet velocity of 2.5x10^{-4} m/s and a 10-mm-wide flow channel.

Dielectrophoresis

Fundamentals: DEP arises from the interaction of a non-uniform electric field with induced dipoles within microparticles, affecting both neutral and charged microparticles. The DEP force is dependent on the permittivity difference of the microparticle and the fluid, the field gradient, the configuration of the electrodes, and the frequency, as illustrated in Equation 8.

Equation 8. $$\boldsymbol{F_{DEP} = 2\pi a^3 \varepsilon_m Re[K(\omega)]\nabla|E|^2}$$

Where

a = Particle radius

ε_m = Permittivity of Medium

$$K(\omega) = Clausius - Mossotti\ Factor = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* - 2\varepsilon_m^*}$$

ε_p^* = Complex Permittivity of the Particle

ε_m^* = Complex Permittivity of the Medium

$$\varepsilon^* = \text{Complex Permittivity} = \varepsilon - \frac{j\sigma}{\omega}$$

ε^* = Real Permittivity (Dielectric Constant)

σ = Electrical Conductivity (S/m)

The above complex permittivity, ε^* or dielectric properties, of both the microparticle and the fluid decides how a microparticle polarizes relative to the surrounding medium (fluid) in a non-uniform electric field

Multiphysics 2D Model: As with the magnetophoresis case, the multiphysics model integrates three physics: fluid flow, with velocity and pressure as dependent variables; the electrical field generated by the electrodes outside the fluid, with the vector field as the dependent variable; and microparticle tracing, which accounts for the dielectrophoretic force illustrated in Equation 8, along with other concurrent forces such as convective and viscous drag, buoyancy, and gravity. All these forces are calculated for each microparticle in the flow. The model is solved in transient mode for microparticle-tracing physics, as forces on the microparticles and their positions change over time. The fluid flow is modeled in stationary mode, assuming that the microparticles are small enough not to influence the flow pattern or velocity.

Figure 37 illustrates the model outcome results of a) electrode configuration, b) fluid flow velocity, c) electrical potential generated by the electrodes, and d) electrical field that includes two magnified images of the pitch spots at the edges of the electrodes, leading to the large electrical field gradients, resulting in a large DEP force on the microparticles within these spots. As in the above magnetophoresis case, the multiphysics model's domains include a single flow channel and the electrodes along the channel, as illustrated in Figure 37. The key domain parameters include the dimensions (width and length) of the flow channel, the size of the electrodes, along with the number and position/pitch, and the applied electrical potential to them. The preliminary study was based on the effect of one domain parameter (width of the flow

channel), the number of electrode domains in series, the electrical potential applied to them, and one dependent variable (inlet flow velocity).

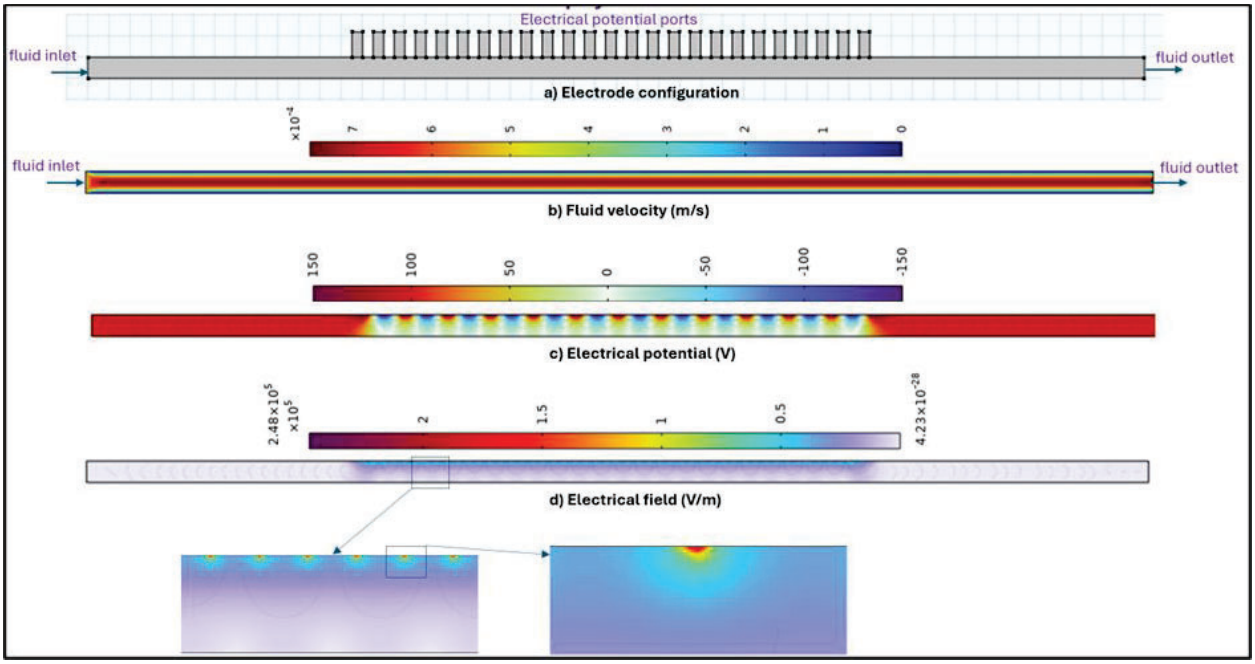


Figure 37. Model-based EP outcome results of the a) electrode configuration b) fluid flow velocity, c) electrical potential generated by the electrodes, and d) electrical field.

Selected Multiphysics 2D Model Case: For PTFE microparticles in DI water fluid, with a diameter of 0.04 mm (40 µm), and a flow channel length of 500 mm, a preliminary study case (no optimization) was conducted to find the inlet fluid velocity, the flow channel width, number of electrodes with a predetermined dimension, and the electrical potential applied to the electrodes needed to remove the microparticles. The study found that an inlet flow velocity of 2.5×10^{-4} m/s and an applied voltage of 200 V to 25 electrodes resulted in the complete separation of the microparticles, as illustrated in Figure 38.

As illustrated in Figure 38, all inlet PTFE microparticles with a 40-µm-diameter in DI water fluid are essentially pulled down via DEP when 200 V is applied to 25 electrodes, using a $2.5x10^{-4}$ m/s fluid inlet velocity (1.5 mL/min) and a 10-mm width flow square flow channel. The end of the flow channel may be split into two channels to generate two flows: one microparticle-depleted flow and the other with microparticles.

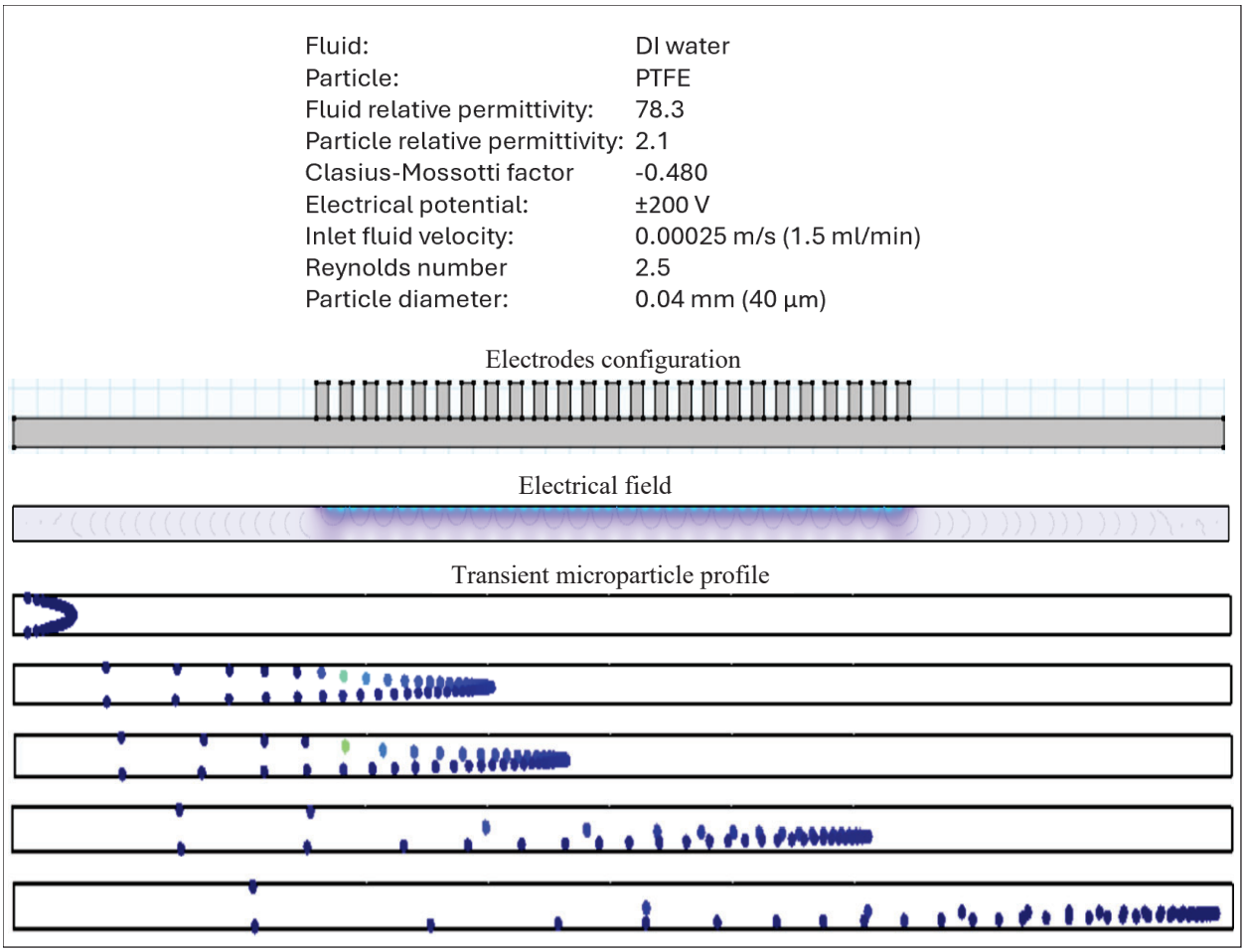


Figure 38. Dielectrophoretic separation of 40-µm-diameter PTFE microparticles in DI water fluid with 2.5x10-4 m/s inlet fluid flow and 200 V applied to 25 electrodes in series

Electrophoresis:

Fundamentals: The electrophoretic force is applied to a charged microparticle when it is in an electric field. Electrophoretic force F is calculated as:

Equation 9. $$\boldsymbol{F = 3\pi\mu d_p v_e}$$

Where

µ = Fluid Viscosity

d_p= Particle Diameter

v_e = Electrophoretic Velocity = u_eE

u_e = Electrophoretic Microparticle Mobility = $\frac{\varepsilon\zeta}{\mu}$

ε = Fluid Permittivity

ζ = Particle Z Potential

µ = Fluid Viscosity

E = Electrical Field

Table 18. Summary Comparison of Forces Generated via DEP and EP summarizes and compares both electrical-field-driven forces.

Table 18. Summary Comparison of Forces Generated via DEP and EP

Feature	Electrophoresis	Dielectrophoresis
Requires Net Charge?	Yes	No (works with neutral particles)
Field Type	Uniform	Non-uniform
Force Direction	Along field	Toward or away from high-field regions
Works at Isoelectric Point (IEP)?	No (zero force)	Yes
Depends on	Zeta Potential	Polarizability and field gradient
Common Use	Separation based on Charge	Separation based on size/composition

Multiphysics 2D Model: The earlier multiphysics model used in the dielectrophoretic study, with its three physics (Figure 4) is applied to the electrophoretic case since both forces act on the microparticle under an electrical field. The dielectrophoretic force is driven only by the field gradient, as shown in Equation 8. In contrast, the electrophoretic force, even in a uniform field, is driven by the electrical field, as shown in Equation 9. For the electrophoretic case, the setup remains the same as in the earlier dielectrophoretic study: PTFE microparticles in DI water, with a 40-µm microparticle diameter, 10-mm-wide flow channels, and an inlet fluid velocity of 0.00025 m/s. 9–10. Figure 39 summarizes the model-based transient profile of the PTFE microparticles in water with a pH of 7, which induces a charging Zeta potential of -30 mV, as shown in Table 19.

Table 19. Zeta Potential of PTFE Microparticles in Pure Water

pH	Zeta Potential (mV)	Sign
3	~ 0 to 5	Near IEP
5	~ -15	Negative
7	~ -30	Negative
9	~ -45	Negative
11	~ -50	Negative

With this setup at pH 7, the charge on the PTFE microparticles does not generate enough electrophoretic force to separate them. Increasing the pH from 7 to 11 raises the Z potential from -30 to 50 mV (see Table 19). Still, the model shows no significant increase in the electrophoretic force capable of pulling the microparticles down and separating them. PTFE microparticles in water can be treated to carry much higher surface charges. Approaches include: 1) adding anionic surfactants, such as sodium dodecyl sulfate, to increase negative surface charge, and 2) adding cationic polymers, such as poly(diallyldimethylammonium chloride), for strong positive charging. While dielectrophoretic force pulls the microparticles toward low-field regions (opposing force, since $\varepsilon_{PTFE} \ll \varepsilon_{water}$), the electrophoretic force pulls them toward the anode (due to $\zeta = -30$ mV). Both forces act on microparticles simultaneously. Therefore, these forces usually are not aligned; in fact, they typically act in different directions unless the field geometry happens to align them.

Fluid:	DI water
Particle:	PTFE
Water Z potential @ pH=7	-30 mV
Water permittivity	8.85E-12 F/m
Electrophoretic mobility	-2.98E-10 m^2/V.s
Electrical potential:	±200 V
Inlet fluid velocity:	0.00025 m/s (1.5 ml/min)
Particle diameter:	0.04 mm (40 µm)

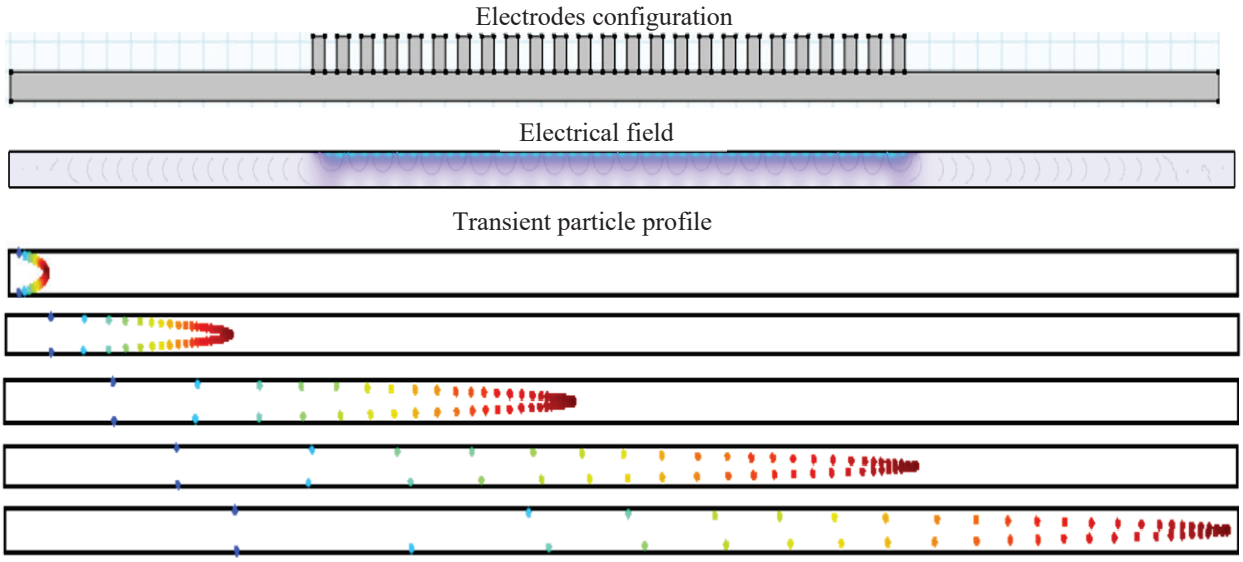


Figure 39. Electrophoresis on 40-µm-diameter PTFE particles in DI water fluid with pH = 7 (Zeta potential = -30 mV), 2.5x10-4 m/s inlet fluid flow, and 200 V applied to 25 electrodes in series.

Summary and Conclusions:

Gravity does not play a significant role in microparticle separation because it is effectively counterbalanced by buoyancy and Stokes drag. For aluminum microparticles suspended in SAE 5W fluid, separation can be achieved through magnetophoresis, as demonstrated for 40 µm particles. In contrast, PTFE microparticles in deionized water require electric-field–based mechanisms, with both DEP and EP serving as viable approaches for particles of similar size. Raising the water pH from 7 to 11 increases the surface charge of PTFE, but this adjustment only marginally enhances electrophoretic separation. DEP exerts a more pronounced influence than EP for PTFE particles; however, achieving effective separation requires careful electrode configuration to ensure proper alignment of the forces. Reducing the electrode pitch further strengthens the dielectrophoretic effect by creating a more uniform and continuous electric field gradient, which in turn allows for lower applied electrical potentials while maintaining the same separation outcome. Operating with AC fields in the range of ~100 kHz to 1 MHz promotes DEP while suppressing EP and minimizing Faradaic or electrolysis reactions. Alternatively, applying low-frequency alternating current (AC) or introducing a slight direct current (DC) offset can generate a combination of EP and DEP forces that reinforce each other, though this approach carries the risk of excessive heating. Future research should focus on optimizing electrode geometries, tuning AC frequencies, and developing hybrid EP–DEP strategies to further improve separation efficiency.

7.4.2.2 ICAF Design

The ICAF prototype was developed in parallel with the analytical evaluation and was intended to combine both EP and DEP strategies while incorporating a method for purging accumulated contaminants. As shown in Figure 40, the device consists of a reservoir, pump, control valve, and contaminant release valve connected in line.

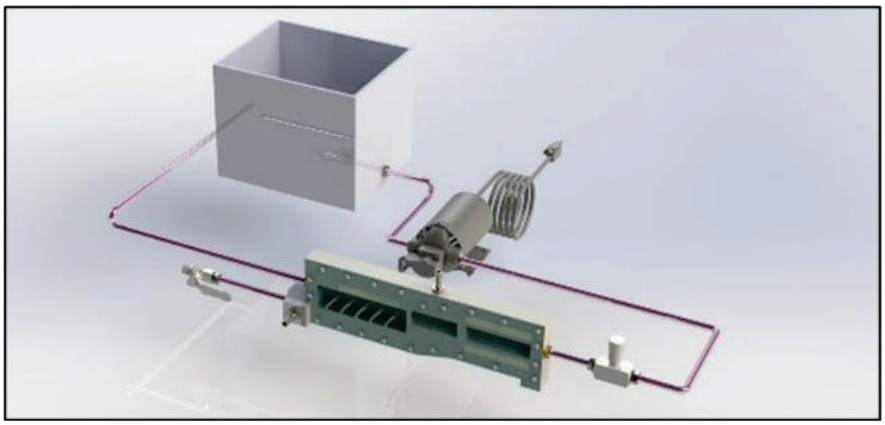


Figure 40. Computer-aided draft (CAD) model of the ICAF device.

The internal layout includes three primary regions, along with a clear polycarbonate viewing window that enables observation of particle behavior throughout the process (Figure 41).

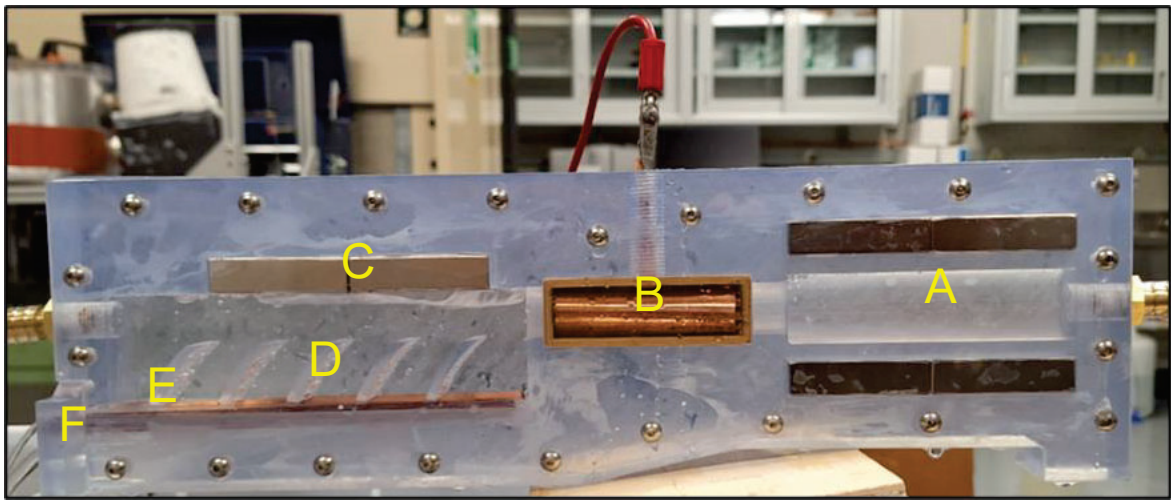


Figure 41. ICAF Device Overall Assembly.

In Section A (Figure 42), an initial magnetic stage containing four neodymium magnets (96-lb pull strength each) was added to remove ferrous contaminants that could otherwise interfere with evaluation of the EP/DEP concept, particularly in Section C. After passing through Section A, particles entered the charged copper tube bundle (Section B in Figure 41). Each tube has a 3/16" outer diameter and is electrically coupled to the larger outer copper tube. A soldered wire passes through the top of the structure and is potted with epoxy to maintain a watertight seal. This tube bundle constrains the flow to maintain laminar conditions and induces charge transfer to the particles through physical contact.

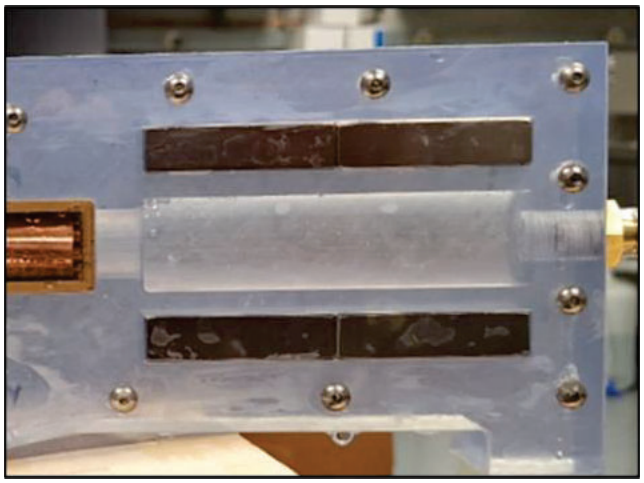


Figure 42. Initial stage of ICAF.

After exiting the tube bundle, charged particles interact with two neodymium magnets in Section C and then with the fin structures in Section D (Figure 41). The fins (Figure 44) guide particles toward the bottom of the device where the positively charged collection plates (Section E) are located. These plates angle downward to direct the particles toward the purge valve (Section F), where they can be expelled to a collection beaker.

Figure 43. Charged copper tubes bundle within ICAF (side view).

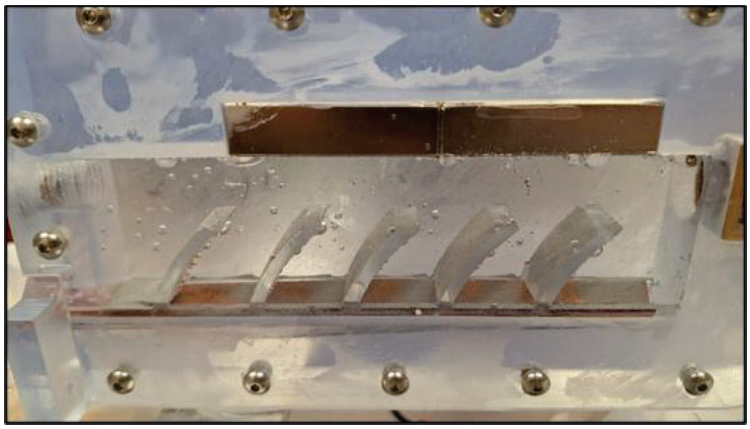


Figure 44: Fin design to guide powder particles away from magnet into collection plates.

The housing was additively manufactured from 11122 SLA resin, and the viewing window was laser cut. The holes around the parameter were printed within the design and heat-set threaded inserts were fitted into the resin design. The larger threads for the barbed hose connections were additively manufactured into the design. Threaded holes were printed directly into the design and fitted with heat-set inserts. Larger threads for hose connections were also printed in place. After installing the magnets, the window was sealed using RTV silicone as a temporary gasket and then fastened. A partially assembled view of the prototype is shown in Figure 45.

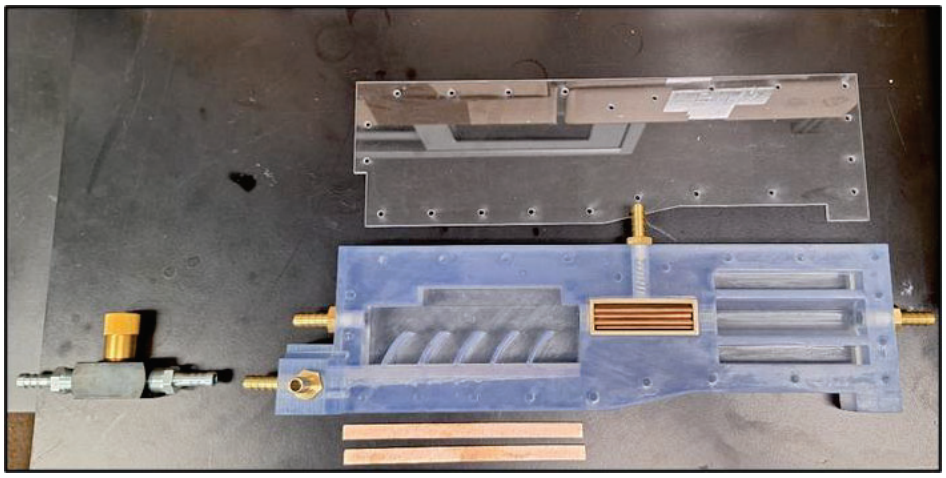


Figure 45: Assembly of ICAF prototype

7.4.2.3 Experimental Setup

To begin testing, DI water was filled into the reservoir bin in Figure 46. An initial run with DI water was run to test for seal integrity, and adjustment of flow velocity with the throttle valve and pump rheostat. To determine the corresponding pump volumetric flow rate in mL/s, results from Section 7.4.2.1 were used as a starting point. This model determined that for a 40-µm particle size, a velocity of .00025 m/s in a 10-mm channel was optimal under the electrical fields that were most realistic without significant electrolysis and use of permanent magnets. However, a flow rate this low was below the capability of the pump and throttle valve.

Additionally, previous analytical models used a particle velocity of .005 m/s, or nearly 2x the velocity of the model, for full separation. Based on the available PTFE powder, the smallest agglomerated particle range of 1-5 µm was used for testing. This most closely simulated the 0.2-µm PTFE particles in fluorinated lubricants such as Braycote or Krytox [141]. The calculated cross-sectional area of the main chamber in the prototype, between Sections C and D of Figure 41, was 4.8387 cm^2. With the calculated cross-sectional area and goal particle velocity of .005 to .007 m/s, a target volumetric flow rate between 2.5 to 3.5 mL/sec was achieved by adjusting of the pump rheostat. Determination of the approximate volumetric flow rate was done by timing the filling of a 25-mL graduated cylinder three times. The fill times were 7.21, 7.97, and 7.59 seconds. These fill times average to 7.59 seconds and a calculated volumetric flow rate of 3.29 mL/s.

Flow rate was significantly easier to adjust using the throttle valve than the pump rheostat as pump voltage neared its operational lower limit. Careful balance between the pump and throttle valve was important to prevent any clumping of particles at the throttle valve inlet. For future prototypes, a lower capacity and more adjustable pump would be recommended for easier

adjustment. Additionally, for the final tests, the throttle valve was removed and just the pump rheostat was used to adjust flowrate.

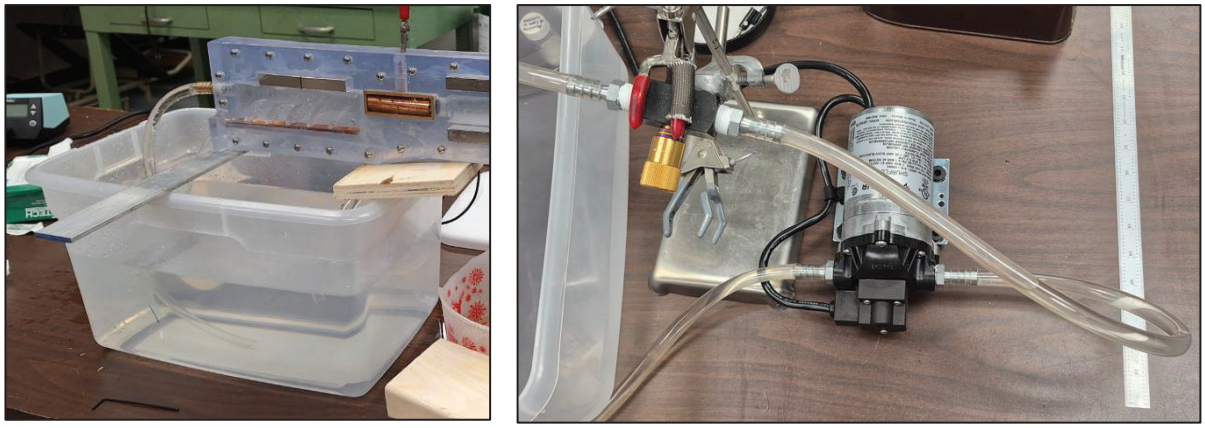


Figure 46: Reservoir bin filled with water with pump inlet line (Left) and pump/control valve (Right).

There are two terminals in the ICAF device where a power supply was hooked up. The lead that was connected to the copper tubing was negatively charged via an alligator clip. The collection plates at the bottom of the device were positively charged to attract the negatively charged particles.

Before running any tests, the ICAF device was always cleaned and rinsed of any previous test. Once the device was cleaned, the alligator clips were connected. Next, the test powder was mixed with the DI water in the bin and the pump was turned on. Once the pump was on for several minutes, laminar flow within the device was achieved. When the flow was very laminar and the particles were visible, the powder supply was turned on. Several power supplies were tested ranging from 60 V to 300 V. After the power supply was on, the particle behavior could be viewed.

7.4.2.4 Results

Original Configuration

Various configurations and powder types were evaluated on the ICAF prototype. EP and DEP interactions of larger non-ferrous metallic powder (aluminum) was believed to be unsuccessful due to gravity. Future evaluation with smaller non-ferrous powders is recommended. When evaluating the prototype with the PTFE powder, while the average particle size reported by the manufacturer was 1-5 µm, there appeared to be a significant agglomeration into larger particles. These larger particles experienced hydrophobic behavior and did not mix well into the main reservoir. Additionally, any larger particles tended to clog the flow into the throttle valve and as stated above, the throttle valve had to be removed for the final tests. Another critical aspect of the prototype is flow equilibrium or balance. Any leak from the main cover, any potted electrical connection or fitting or valve would throw the laminar flow out of balance. All testing was conducted at 60 V, as more voltage only induced electrolysis. Various orientations of the magnets were tested to include rotating them as seen in Figure 47.

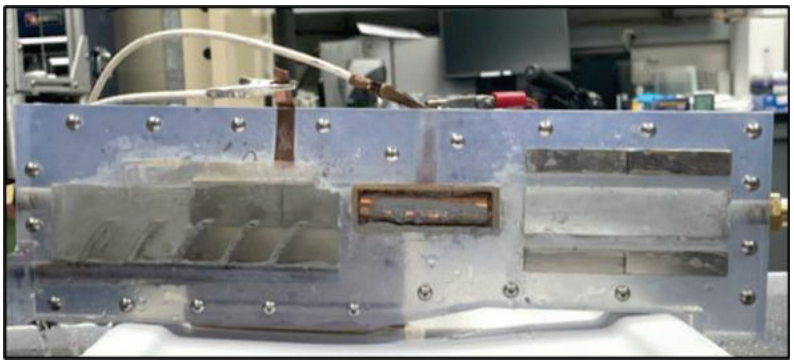


Figure 47: ICAF during operation with rotated magnets.

The final test of the prototype with PTFE powder showed consistent movement of what can be considered a visual, average size of the particles that made it through the copper tube bundle and into the main region with the fins. Particles that were larger tended to stay somewhat buoyant and get stuck in Section A (Figure 42). As the particles moved into the region directly past (below) Section C (Figure 41), they curved upward. The particles that were closer to the surface of the magnets appeared to get temporarily stuck on the boundary layer of the magnet. Particles that started their laminar flow separated at distances of approximately 1.5 to 4 mm appeared to curve upwards but did not adhere to the magnet. The movement of the particles or curving effect appeared to primarily depend on a combination of particle size and distance from the magnet given the flow rate.

A new version of the concept with just the magnetic field was attempted with a glass tube connected with Tygon® tubing to the pump. This concept allowed for easier control of the magnet position and visual observation, however due to the small diameter of the glass tube and the minimum flow rate the pump could achieve, a low enough particle velocity was not able to be achieved and therefore not fully evaluate the ICAF principle.

To further evaluate and mature the ICAF concept, several improvements to future test setups and prototypes are recommended. A pump capable of lower and more precisely controlled flow rates would enable testing conditions closer to the analytical model, particularly for small particle sizes. Improved methods for dispersing hydrophobic or agglomeration-prone powders would help ensure representative particle behavior. Enhancing sealing strategies—such as permanent gaskets, molded-in electrical feedthroughs, or rigidized window interfaces—would help maintain consistent laminar flow. Finally, developing modular test sections (e.g., interchangeable magnet configurations, wider flow channels, or adjustable tube-bundle geometries) would allow systematic exploration of EP and DEP effects across a broader range of particle sizes and flow conditions. These refinements would provide a more controlled environment for assessing the separation efficiency and overall feasibility of the ICAF approach.

7.5 Costs to Implement New Technologies

In evaluating the adoption of new precision cleaning technologies, it is essential to provide stakeholders with a clear understanding of the anticipated costs associated with each option. This section presents a qualitative estimate of the rough costs for each technology under consideration, with cost approximations broken down into three primary categories: equipment cost, facilities cost, and operating cost. For each technology, we assign a relative cost range using a ‘dollar sign’ ($–$$$$$) system, where a greater number of dollar signs indicates a higher

expected cost within that category. These estimates are intended to provide a comparative overview rather than precise budget figures, recognizing that actual costs may vary significantly depending on facility size, throughput requirements, and site-specific implementation factors. Where possible, uncertainties and potential cost drivers, especially for novel or emerging technologies, are noted to guide future planning and risk assessment.

Table 7.5-1. Qualitative Cost Comparison of New Cleaning Technologies

Technology	Equipment Cost	Facilities Cost	Operating Cost	Key Cost Drivers
Solvent Vapor Degreasing	$$$	$$$	$$$	Moderate equipment and facility upgrades; high solvent losses drive operating cost
Solvent Vacuum Degreasing	$$$	$$$	$$$	Cleaning is highly automated and customizable. Extremely low solvent losses but potential for higher energy demands used for cooling.
Aqueous Cleaning Systems	$$$	$$$	$$$	High facility investment for baths, drying, and waste management
Supercritical CO2 Cleaning	$$$$	$$$$	$	High initial capital; low waste stream; safety systems required.
Cryogenic Aerosol Cleaning	$$$	$$$	$$$	Specialized equipment; robust environmental controls needed.
Plasma/UV-Ozone Cleaning	$$$	$$	$	Lower facility cost; best for final cleaning, not gross removal.
Magnetically Optimized Fluids (MOF)	$-$$	$-$$	$	Still experimental; cost highly uncertain.
Induced Charge Active Filtration (ICAF)	$-$$	$	$	Prototype stage; potential for solvent life extension, and filter cost savings. Low facility and operating cost expected. Initial equipment cost variable based on scalability required.
Cost Level Legend				
Symbol	**Relative Cost Level**	**Cost Description**		
$	Very Low	Minimal investment; <$10k or negligible		
$$	Low	Low investment; $10k–$50k		
$$$	Moderate	Moderate investment; $50k–$250k		
$$$$	High	High investment; $250k–$1M		
$$$$$	Very High	Very high investment; >$1M		

Note: These cost ranges are qualitative and intended for comparative purposes only. Actual costs will depend on facility size, throughput, and specific implementation requirements. For emerging technologies (MOF, ICAF), cost estimates are especially uncertain and may change as the technologies mature

8.0 Findings, Observations, and NESC Recommendations

8.1 Findings

Task 1A: Feasibility of Implementing Solstice Performance Fluid (PF) Usage Access Agency/External Entities for Precision Cleaning

F-1. Adoption of Solstice PF/PF-HP for precision cleaning at NASA SSC and MAF, with minimal facility modifications, was successful. (Sections 7.1.2, 7.1.3, 7.1.4)

F-2. Capture and recycling of used Solstice PF/PF-HP from closed loop-style cleaning systems with acceptable recovery is successful. (Sections 7.1.3, 7.1.4)

F-3. Solstice PF/PF-HP may not be practical for large, high-throughput precision cleaning facilities due to its drastically different physical properties (i.e., boiling point, vapor pressure, and solubility) from currently used solvents, incurring high capital investment in new equipment. (Section 7.1.4)

F-4. Vapor degreasers designed for Novec HFE-7100, or other solvents with properties (boiling point and vapor pressure) significantly different than Solstice PF/PF-HP are not compatible with Solstice PF/PF-HP, requiring significant modification or replacement. (Section 7.1.4)

Task 1B: Evaluation of 'Drop-In' Replacement Candidates for Novec HFE-7100

F-5. Nine of the twelve selected candidates met baseline NVR requirements for precision cleaning. (Section 7.2.3)

F-6. Amolea AS300 and solvent candidates containing tDCE had superior hydrocarbon miscibility over other candidates; other candidates performed in line with HFE-7100. (Section 7.2.4)

F-7. Amolea AS-300 was found to perform significantly better than other non-tDCE-containing candidates when removing silicone vacuum grease. (Section 7.2.6)

F-8. Amolea AS-300 and Opteon SF33, followed by BestSolv Sierra, were determined to perform the best at removing a mixed contaminant challenge (hydrocarbon oils and fluorinated greases) on small, complex geometry parts in the lab scale testing performed. (Section 7.2.7)

F-9. 4340 Low Alloy Steel had corrosion in excess of allowable levels after contact with BestSolv Sierra, Ensolv Fluoro IC, Amoela AS-300, and Opteon SF30 in both full immersion and vapor exposure studies. (Section 7.2.7, Appendix A)

F-10. Significant corrosion (> allowable mpy) was not noted for metals other than 4340 LAS exposed to the solvent candidates in both full immersion and vapor exposure studies. (Section 7.2.7, Appendix A)

F-11. All candidate solvents and HFE-7100/Promosolv DR3 had various levels of deleterious effect on multiple soft goods. (Section 7.2.7, Appendix B)

F-12. Testing revealed Opteon SF33 and BestSolv Sierra have AIT values above 204 °C (400 °F), making them more favorable for oxygen system cleaning. (Section 7.2.7, Appendix C)

F-13. Testing of Amolea AS-300 revealed it has an AIT below 204 °C (400 °F), making it a less favored solvent for enriched oxygen system cleaning. (Section 7.2.7, Appendix C)

Task 2: Identification and Initial Testing of Alternative Precision Cleaning Technologies

F-14. Aqueous cleaning systems have demonstrated effective removal of a broad range of contaminants but require significant facility modifications, increased water and energy consumption, and careful management of rinse water quality to avoid recontamination. (Section 7.3)

F-15. $SCCO_2$ cleaning provided excellent performance for nonpolar and fluorinated contaminants, but poor removal of particulate contamination. The high capital cost,

operational complexity, and safety requirements (high-pressure, CO_2 handling) limit near-term adoption for most NASA facilities. (Section 7.3)

F-16. Cryogenic aerosol cleaning (CO_2 snow, Ar/N_2) effectively removed particulates from sensitive surfaces without liquid waste but was less effective for heavy organic or adherent contamination and requires robust environmental controls for safe operation. (Section 7.3)

F-17. Plasma and UV-O_3 cleaning technologies showed promise for final cleaning and surface activation but are not suitable for contamination removal and require pre-cleaning steps for most aerospace hardware. (Section 7.3)

F-18. Magnetically Optimized Fluids (MOF) did not demonstrate significant improvements in cleaning efficacy or solvent properties under the tested conditions; further research is needed to optimize field strength, exposure time, and solvent selection. (Section 7.4.1)

F-19. The Induced Charge Active Filtration (ICAF) prototype qualitatively demonstrated visible separation of certain non-metallic, non-ferrous particulates from cleaning fluids without the use of traditional filters. This visual effect was evident during physical testing. (Section 7.4.2)

F-20. The ICAF analytical model provided a quantitative assessment of particle transport and separation within the flow path, showing strong sensitivity to particle size, flow rate, and applied field configuration. (Section 7.4.2)

F-21. None of the alternative cleaning technologies evaluated are currently ready for direct replacement of solvent-based cleaning in high-throughput, mission-critical NASA applications without further maturation and facility adaptation. (Sections 7.3, 7.4)

8.2 Observations

Task 1A: Feasibility of Implementing Solstice Performance Fluid (PF) Usage Access Agency/External Entities for Precision Cleaning

O-1. Solstice PF/PF-HP implementation reduced regulatory risk for facilities that adopted it to replace AK225. (Section 7.1.4)

O-2. Cleaning processes utilizing Solstice PF/PF-HP require detailed planning and monitoring to ensure minimal loss. (Section 7.1.4)

O-3. On-site distillation and recycling of Solstice PF/PH-HP reduces waste and cost but adds operational complexity. (Section 7.1.3)

Task 1B: Evaluation of 'Drop-In' Replacement Candidates for Novec HFE-7100

O-4. Solvents not considered 'top performers' for the mixed contaminant challenge may still be useful for specific contaminants and use applications. (Sections 7.2.5, 7.2.6)

O-5. Certain solvents have lower exposure limits than HFE-7100, possibly requiring changes to ventilation or PPE. (Section 7.2.6)

O-6. While Amolea AS-300 has less favorable properties for oxygen system compatibility overall, it may be possibly considered with additional solvent removal requirements and may still be acceptable for non-oxygen-enriched hardware (e.g., Breathing air/Compressed air systems). (Section 7.2.7)

O-7. An overall balance in cleaning performance, system/material compatibility, facility design, and safety/environmental considerations must be made when selecting which alternative solvent to utilize. (Sections 7.2.6, 7.2.7)

O-8. Two of the three that failed had unacceptable NVR levels likely caused from storage containers that could be remedied.

Task 2: Identification and Initial Testing of Alternative Precision Cleaning Technologies

O-9. Aqueous and $SCCO_2$ cleaning systems are environmentally favorable and reduce regulatory risk but require substantial investment in new equipment, facility modifications, and operator training. (Section 7.3)

O-10. Dry cleaning technologies (cryogenic aerosol, plasma, UV-ozone) generate minimal liquid waste and are attractive for sensitive or complex hardware, but their cleaning mechanisms are limited to specific contaminant types. (Section 7.3)

O-11. Vacuum solvent degreasing can obtain near zero solvent loss with the system being contained, however the technology has higher initial capital equipment costs and for lower boiling point solvents, operational costs may be higher for solvent refrigeration. (Section 7.3)

O-12. The scalability and throughput of alternative cleaning technologies vary widely; aqueous and $SCCO_2$ systems can be scaled for large components, while plasma and UV-ozone are best suited for small parts or final cleaning steps. (Section 7.3)

O-13. Implementation of alternative cleaning technologies may require updates to facility safety protocols, waste management procedures, and environmental monitoring systems. (Section 7.3)

O-14. The ICAF device offers potential for reducing filter waste and maintenance costs in high-particulate environments, but its operation is sensitive to flow stability, voltage, and particle agglomeration. (Section 7.4.2)

O-15. MOF and ICAF technologies align with NASA's long-term sustainability and compliance goals but require further development and pilot-scale demonstration. (Sections 7.4.1, 7.4.2)

O-16. The lack of ability to perform traditional cleanliness verification for some alternative technologies (e.g., supercritical CO_2, plasma) limits adoption feasibility when considering minimization and elimination of solvent use. (Section 7.3)

O-17. Early engagement with regulatory, safety, and facility stakeholders is critical to successful adoption and integration of new cleaning technologies. (Section 7.3)

8.3 NESC Recommendations

The following NESC recommendations are directed to HFE 7100 users, as well as the NASA Centers and Programs responsible for specifications and standards that involve HFE 7100 precision cleaning processes and associated testing requirements.

Task 1A: Feasibility of Implementing Solstice Performance Fluid (PF) Usage Access Agency/External Entities for Precision Cleaning

R-1. Consider use of Solstice PF/PF-HP as an alternative for Novec HFE-7100 in small-to-medium throughput facilities where equipment is compatible or modifications are not cost-prohibitive. (F-1, F-2, F-3, F-4, O-1, O-2, O-3)

Task 1B: Evaluation of "Drop-In" Replacement Candidates for Novec HFE-7100

R-2. Large-scale or high-throughput facilities should seek drop-in solvents with properties closer to HFE-7100 to minimize disruption and capital expense. (F-3, F-4, F-5, F-6, F-7, F-8, O-4, O-7)

R-3. Review cleaning efficacy for specific end use needs (e.g., hydrocarbon contamination, fluorinated contamination, mixed contamination, etc.), materials/system compatibility, compatibility with existing cleaning hardware, and facility/safety requirements before adopting any replacement solvent. (F-5, F-6, F-7, F-8, F-9, F-10, F-11, F-12, F-13, O-4, O-5, O-6, O-7, O-9)

R-4. For oxygen system cleaning, use solvents with AIT >204 °C when possible. (F-12, F-13, O-7)

R-5. Implement secondary flushing or other extra monitoring precautions (e.g., hydrocarbon lockup) when using solvents with lower oxygen compatibility in oxygen-enriched systems. (F-13, O-7)

R-6. Update NASA standards/specs to allow "molecularly equivalent products" to Novec HFE-7100 and new drop-in options with clear purity and compatibility requirements. (F-5, F-6, F-7, F-8, F-9, F-10, F-11, F-12, F-13, O-4, O-5, O-6, O-7, O-9)

Task 2: Identification and Initial Testing of Alternative Precision Cleaning Technologies

R-10. Continue pilot-scale demonstrations and facility trials of aqueous, $SCCO_2$, and dry-cleaning technologies to mature their readiness for NASA applications. (F-14, F-15, F-16, F-17, F-18, F-19, F-20, O-10, O-11, O-12, O-13, O-14, O-15, O-16, O-17, O-18)

The following NESC recommendations are identified as areas for future study and development to support long-term obsolescence planning and potential updates to NASA's precision cleaning processes. These recommendations highlight technologies and practices that warrant further evaluation to ensure readiness for future changes in cleaning requirements and standards.

Future Work, Task 2: Identification and Initial Testing of Alternative Precision Cleaning Technologies

R-7. Update NASA standards and specifications to incorporate successful alternative cleaning technologies, including guidance on facility modifications, safety, and environmental compliance. (F-14, F-15, F-16, F-17, F-18, F-19, F-20, O-10, O-11, O-12, O-13, O-14, O-15, O-16, O-17, O-18)

R-8. Invest in further research and development of MOF and ICAF technologies, including optimization of field strengths, flow channel design, and contaminant types. (F-18, F-19, F-20, O-16, O-17)

R-9. Develop and validate standardized cleanliness verification protocols for alternative cleaning technologies to ensure compatibility with NASA ground and flight hardware requirements. (F-17, O-18)

R-11. Engage facility, safety, and environmental stakeholders early in the evaluation and adoption process for new cleaning technologies to ensure smooth transition and regulatory compliance. (O-19)

R-12. Monitor emerging regulatory trends and maintain a diversified risk mitigation strategy that includes both solvent-based and solvent-free cleaning options. (O-10, O-11, O-12, O-13, O-14, O-15, O-16, O-17, O-18, O-19)

9.0 Alternate Technical Opinion(s)

No alternate technical opinions were identified during the course of this assessment by the NESC assessment team or the NESC Review Board (NRB).

10.0 Other Deliverables

A standalone report focused specifically on the feasibility of implementing use of Solstice PF at Kennedy Space Center's CRCA Facility was provided to Exploration Ground Systems in February 2024 (Report # NASA-05586) as a deliverable for a Center-owned risk on the obsolescence of Novec HFE-7100.

11.0 Recommendations for the NASA Lessons Learned Database

No recommendations for NASA lessons learned were identified as a result of this assessment.

12.0 Recommendations for NASA Standards, Specifications, Handbooks, and Procedures

The assessment team recommends that owning Centers and Programs review existing NASA specifications and standards that include HFE-7100 precision cleaning fluid processes and testing requirements for the following:

a. Update of tables for Novec HFE-7100 to include allowance of "molecularly equivalent products" so as to not limit to the brand name.

b. Update to allow use of newly identified drop-in replacement options from this assessment should the Center/Program determine them acceptable. Updates should also include a table with purity testing requirements.

Additionally, it is recommended that materials compatibility data for metals and soft goods presented in this report be incorporated into any Agency, Center, and Program-owned references for end users to access.

13.0 Definition of Terms

Corrective Action	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.
Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their

	independent analyses, tests, inspections, and/or reviews of technical documentation.
Lesson Learned	Knowledge, understanding, or conclusive insight gained by experience that may benefit other current or future NASA programs and projects. The experience may be positive, such as a successful test or mission, or negative, as in a mishap or failure.
Observation	A noteworthy fact, issue, and/or risk, which is not directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support.
Problem	The subject of the independent technical assessment.
Proximate Cause	The event(s), including any condition(s) that existed immediately before the undesired outcome, that directly resulted in its occurrence.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Root Cause	One or multiple causes (including adverse or unplanned events, conditions, or organizational factors) that contributed to or created the proximate cause(s) and subsequent undesired outcome and, if eliminated or modified, should have prevented the undesired outcome.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides a detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions.

14.0 Acronyms and Nomenclature List

°C	Degrees Celsius
°F	Degrees Fahrenheit
”	Inch
µL	Microliter
µm	Micrometer
%	Percent
σ	Standard Deviation
AC	Alternating Current
AIM	American Innovation and Manufacturing
AIT	Autoignition Temperature
Al	Aluminum
APG	Alkyl Polyglycoside
Ar	Argon
atm	Atmosphere
BP	Boiling Point
Buna N	Acrylonitrile Butadiene Rubber

CAS	Chemical Abstract Service
CCP	Commercial Crew Program
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
cm	Centimeter
cm^2	Square Centimeter
CO_2	Carbon Dioxide
cP	Centipoise
CRCA	Component Refurbishment and Chemical Analysis Facility
Cu	Copper
D_2	Molecular Deuterium
DC	Direct Current
DEP	Dielectrophoresis
DI	Deionized
DoD	Department of Defense
EGS	Exploration Ground Systems
EP	Electrophoresis
EPA	Environmental Protection Agency
EPDM	Ethylene Propylene Diene Monomer Rubber
EU	European Union
FEP	Fluorinated Ethylene Propylene
FFKM	Perfluoroelastomer
FKM	Fluoroelastomer
ft^2	Square foot
g	gram
GRC	Glenn Research Center
GWP	Global Warming Potential
H_2	Molecular Hydrogen
HCFC	Hydrochlorofluorocarbon
He	Helium
HEPA	High Efficiency Particulate Air
HFC	Hydrofluorocarbon
HFE	Hydrofluoroether
HFE-7100	Novec 7100 Engineering Fluid
HFE-7200	Novec 7200 Engineering Fluid
HLS	Human Landing System
HP	High Purity Grade
hr	Hour
ICAF	Induced Charge Active Filtration
ID	Internal Diameter
IEST	Institute of Environmental Sciences and Technology
in	Inch
IPA	Isopropyl Alcohol
ISO	International Organization for Standardization
ISS	International Space Station
J	Joule

JSC	Johnson Space Center
K	Kelvin
Kb	Kauri-Butanol Value
kg	Kilogram
kHz	Kilohertz
kJ	Kilojoule
kPa	Kilopascal
KSC	Kennedy Space Center
L	Liter
LAS	Low Alloy Steel
lb	Pound
LCO_2	Liquid Carbon Dioxide
LIB	Laser Induced Breakdown
LSC	Laser Shock Cleaning
LSP	Launch Services Program
MAF	Michoud Assembly Facility
m	Meter
mg	Milligram
MHz	Megahertz
mL	Milliliter
mm	Millimeter
mmHg	Millimeters of Mercury
mN	MilliNewton
MOF	Magnetically Optimized Fluid
mol	Mole
mPa•s	MilliPascal-second
MPCV	Mulipurpose Crew Vehicle
MPY	Mil Per Year
MSFC	Marshall Space Flight Center
mT	Millitesla
mV	Millivolt
N	Newton
N_2	Molecular Nitrogen
NBL	Neutral Buoyancy Laboratory
nm	Nanometer
NVR	Non-Volatile Residue
O*	Atomic Oxygen
O_2	Molecular Oxygen
O_3	Ozone
OD	Outer Diameter
ODP	Ozone Depletion Potential
OSHA	Occupational Health and Safety Administration
P_c	Critical Pressure
PCTFE	Polychlorotrifluoroethylene
PEEK	Polyether Ether Ketone
PF	Performance Fluid

PFAS	Per/Polyfluoroalkeyl Substance
PFBI	Perfluorobutyl Iodide
PFC	Perfluorocarbon
pH	Potential of Hydrogen
PPE	Personal Protective Equipment
ppm	Parts Per Million
ppmw	Parts Per Million by Weight
psi	Pounds per Square Inch
PTFE	Polytetrafluoroethylene
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals
RTV	Room Temperature Vulcanizing
s	Second
SAE	Society of Automotive Engineers
$SCCO_2$	Supercritical Carbon Dioxide
SCF	Supercritical Fluid
SCUBA	Self-Contained Underwater Breathing Apparatus
SLA	Stereolithography Apparatus
SLS	Space Launch System
SS	Stainless Steel
SSC	Stennis Space Center
sq. ft.	Square foot
T_c	Critical Temperature
TCA	1,1,1-trichloroethane
tDCE	Trans-dichloroethylene
Ti	Titanium
TSCA	Toxic Substances Control Act
TWA	Time Weighted Average
UV	Ultraviolet
UV-O_3	Ultraviolet-Ozone
UV-VIS	Ultraviolet-Visible
V	Volt
V/L	Vapor-Liquid
VOC	Volatile Organic Compound
vol	Volume
VP	Vapor Pressure
W	Watt
WLC	Wet Laser Cleaning
w/w	Weight/Weight Percent
WSTF	White Sands Test Facility

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Appendix A. Complete Cleaning Solvent–Metal MPY Matrix

Corrosion results (MPY) for metals exposed to the cleaning solvent candidates are presented below. As previously mentioned, a conservative MPY value of 0.5 g/cm^2 was set as a failing mark for compatibility. ***Failing MPY results are in red text; MPY values with a grey background were determined to be statistical outliers from other replicates in their test group.***

Table 20. 15-5PH Stainless Steel MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	-0.32	-0.03
	2A		-0.31	-0.03
	3A		-0.06	-0.01
	4A	V	-8.51	-0.90
	5A		0.13	0.01
BestSolv Sierra	13A	I	0.75	0.08
	14A		0.38	0.04
	15A		-0.37	-0.04
	16A	V	0.42	0.04
	17A		0.05	0.01
	18A		0.14	0.01
Fluoro IC	1B	I	2.43	0.26
	2B		0.33	0.03
	3B		-0.51	-0.05
	4B	V	0.37	0.04
	5B		0.34	0.04
	6B		1.85	0.19
Opteon SF33	101	I	-0.19	-0.02
	102		-0.14	-0.01
	103		-0.1	-0.01
	104	V	0	0.00
	105		-0.12	-0.01
	106		-0.06	-0.01
AS-300	7A	I	-1.45	-0.15
	8A		-3.33	-0.35
	9A		85.33	8.98
	10A	V	-2.88	-0.30
	11A		-308.5	-32.47
	12A		-2.4	-0.25
Vertrel MCA	19	I	-0.32	-0.03
	20		-0.03	0.00
	21		0.01	0.00
	22	V	0.15	0.02
	23		-0.13	-0.01
	24		-0.06	-0.01
SF-30	7B	I	0.01	0.00
	8B		-0.09	-0.01
	9B		-0.08	-0.01
	10B	V	-0.09	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.14	-0.01
	12B		0.01	0.00

Table 21. 440C Stainless Steel MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	4A	I	0.23	0.02
	5A		-0.23	-0.02
	6A		0.08	0.01
	1A	V	0.36	0.04
	2A		-0.05	-0.01
	3A		0.21	0.02
BestSolv Sierra	13A	I	-0.36	-0.04
	14A		0.28	0.03
	15A		0.41	0.04
	16A	V	-1.53	-0.16
	17A		-0.47	-0.05
	18A		-0.29	-0.03
Fluoro IC	1B	I	-0.19	-0.02
	2B		-0.21	-0.02
	3B		-0.02	0.00
	4B	V	-0.44	-0.05
	5B		0.32	0.03
	6B		0.36	0.04
Opteon SF33	101	I	-0.1	-0.01
	102		-0.25	-0.03
	103		-0.15	-0.02
	104	V	-0.11	-0.01
	105		0.04	0.00
	106		-0.11	-0.01
AS-300	7A	I	0.64	0.07
	8A		1.51	0.16
	9A		2.25	0.24
	10A	V	-0.95	-0.10
	11A		2.61	0.28
	12A		0.2	0.02
Vertrel MCA	19	I	-3.33	-0.35
	20		1.37	0.14
	21		-0.32	-0.03
	22	V	2.05	0.22
	23		-2.87	-0.30
	24		0.56	0.06
SF-30	7B	I	-0.07	-0.01
	8B		-0.12	-0.01
	9B		-0.04	0.00
	10B	V	-0.21	-0.02

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.11	-0.01
	12B		-0.1	-0.01

Table 22. 4340 Stainless Steel MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	4A	I	-0.12	-0.01
	5A		0.79	0.08
	6A		2.4	0.25
	1A	V	1.8	0.19
	2A		-2.53	-0.26
	3A		-0.12	-0.01
BestSolv Sierra	13A	I	18.61	1.96
	14A		28.01	2.95
	15A		-13.11	-1.38
	16A	V	31.93	3.36
	17A		15.45	1.63
	18A		19.57	2.06
Fluoro IC	1B	I	28.25	2.97
	2B		19.79	2.08
	3B		1.42	0.15
	4B	V	-1.69	-0.18
	5B		-0.57	-0.06
	6B		2.34	0.25
Opteon SF33	101	I	0	0.00
	102		-0.24	-0.03
	103		-0.04	0.00
	104	V	0.11	0.01
	105		-0.04	0.00
	106		-0.06	-0.01
AS-300	7A	I	-26.55	-2.79
	8A		-11.68	-1.23
	9A		121.57	12.80
	10A	V	-13.62	-1.43
	11A		-27.56	-2.90
	12A		-110.77	-11.66
Vertrel MCA	19	I	-0.32	-0.03
	20		-0.03	0.00
	21		0.01	0.00
	22	V	0.15	0.02
	23		-0.13	-0.01
	24		-0.06	-0.01
SF-30	7B	I	0.01	3.38
	8B		-0.09	2.26
	9B		-0.08	-4.64
	10B	V	-0.09	-4.74

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.14	-3.67
	12B		0.01	3.15

Table 23. CDA 443 Brass MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	-0.04	0.00
	2A		-0.02	0.00
	3A		-0.09	-0.01
	4A	V	-0.13	-0.01
	5A		-0.07	-0.01
	6A		-0.09	-0.01
BestSolv Sierra	13A	I	-0.06	-0.01
	14A		-0.08	-0.01
	15A		-0.06	-0.01
	16A	V	0.01	0.00
	17A		0	0.00
	18A		-0.03	0.00
Fluoro IC	1B	I	-0.09	-0.01
	2B		-0.09	-0.01
	3B		-0.08	-0.01
	4B	V	-0.14	-0.02
	5B		-0.09	-0.01
	6B		-0.1	-0.01
Opteon SF33	101	I	-0.03	0.00
	102		-0.06	-0.01
	103		-0.05	-0.01
	104	V	-0.11	-0.01
	105		-0.03	0.00
	106		-0.03	0.00
AS-300	7A	I	-0.37	-0.04
	8A		-0.31	-0.03
	9A		-0.24	-0.03
	10A	V	-0.42	-0.05
	11A		-0.18	-0.02
	12A		-0.34	-0.04
Vertrel MCA	19	I	-0.08	-0.01
	20		-0.04	0.00
	21		-0.06	-0.01
	22	V	-0.08	-0.01
	23		-0.04	0.00
	24		-0.05	-0.01
SF-30	7B	I	-0.04	0.00
	8B		-0.05	-0.01
	9B		-0.06	-0.01
	10B	V	-0.05	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.01	0.00
	12B		-0.01	0.00

Table 24. 2219-T0 Aluminum MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	-0.102	-0.04
	2A		-0.093	-0.03
	3A		-0.131	-0.05
	4A	V	-0.112	-0.04
	5A		-0.079	-0.03
	6A		-0.083	-0.03
BestSolv Sierra	13A	I	-0.105	-0.04
	14A		-0.099	-0.04
	15A		-0.115	-0.04
	16A	V	-0.049	-0.02
	17A		-0.044	-0.02
	18A		-0.053	-0.02
Fluoro IC	1B	I	-0.078	-0.03
	2B		-0.18	-0.06
	3B		-0.038	-0.01
	4B	V	-0.057	-0.02
	5B		-0.046	-0.02
	6B		-0.034	-0.01
Opteon SF33	101	I	-0.05	-0.02
	102		-0.041	-0.01
	103		-0.046	-0.02
	104	V	-0.055	-0.02
	105		-0.035	-0.01
	106		-0.051	-0.02
AS-300	7A	I	-0.044	-0.02
	8A		-0.053	-0.02
	9A		-0.085	-0.03
	10A	V	-0.102	-0.04
	11A		-0.023	-0.01
	12A		-0.078	-0.03
Vertrel MCA	19	I	3.024	1.09
	20		0.009	0.00
	21		0.01	0.00
	22	V	0	0.00
	23		0.008	0.00
	24		0	0.00
SF-30	7B	I	-0.025	-0.01
	8B		-0.019	-0.01
	9B		-0.027	-0.01
	10B	V	-0.025	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.066	-0.02
	12B		-0.04	-0.01

Table 25. 6061-T6 Aluminum MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	0.019	0.01
	2A		-0.03	-0.01
	3A		-0.036	-0.01
	4A	V	-0.071	-0.02
	5A		-0.033	-0.01
	6A		-0.052	-0.02
BestSolv Sierra	13A	I	-0.038	-0.01
	14A		0.017	0.01
	15A		-0.005	0.00
	16A	V	0.013	0.00
	17A		-0.039	-0.01
	18A		-0.006	0.00
Fluoro IC	1B	I	-0.049	-0.02
	2B		-0.034	-0.01
	3B		-0.03	-0.01
	4B	V	-0.049	-0.02
	5B		-0.066	-0.02
	6B		-0.164	-0.06
Opteon SF33	37	I	-0.04	-0.01
	38		-0.062	-0.02
	39		0.816	0.28
	40	V	-0.066	-0.02
	41		-0.036	-0.01
	42		-0.038	-0.01
AS-300	7A	I	-0.054	-0.02
	8A		-0.085	-0.03
	9A		-0.218	-0.07
	10A	V	-0.039	-0.01
	11A		-0.111	-0.04
	12A		-0.102	-0.03
Vertrel MCA	19	I	-0.059	-0.02
	20		0.019	0.01
	21		-0.01	0.00
	22	V	-0.025	-0.01
	23		-0.026	-0.01
	24		0.019	0.01
SF-30	7B	I	-0.007	0.00
	8B		-0.019	-0.01
	9B		-0.061	-0.02
	10B	V	-0.038	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.114	-0.04
	12B		-0.087	-0.03

Table 26. 6061-T6 Aluminum with Corrosion Coating MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	19	I	-0.006	0.00
	20		-0.012	0.00
	21		-0.032	-0.01
	22	V	-0.053	-0.02
	23		-0.005	0.00
	24		-0.07	-0.02
BestSolv Sierra	113	I	0.02	0.01
	114		0.044	0.02
	115		0.054	0.02
	116	V	-0.028	-0.01
	117		-0.046	-0.02
	118		0.022	0.01
Fluoro IC	119	I	0.005	0.00
	120		-0.002	0.00
	121		0.011	0.00
	122	V	-0.058	-0.02
	123		-0.012	0.00
	124		-0.043	-0.01
Opteon SF33	107	I	-0.028	-0.01
	108		0.011	0.00
	109		0.02	0.01
	110	V	-0.02	-0.01
	111		-0.017	-0.01
	112		-0.017	-0.01
AS-300	31	I	-0.054	-0.02
	32		-0.085	-0.03
	33		-0.218	-0.07
	34	V	-0.039	-0.01
	35		-0.111	-0.04
	36		-0.102	-0.03
Vertrel MCA	19	I	0.013	0.00
	20		0.004	0.00
	21		-0.003	0.00
	22	V	-0.032	-0.01
	23		-0.042	-0.01
	24		0.006	0.00
SF-30	101	I	0	0.00
	102		-0.042	-0.01
	103		-0.012	0.00
	104	V	-0.034	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	105		0.011	0.00
	106		-0.015	-0.01

Table 27. 7075-T6 Aluminum with Corrosion Coating MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	-0.053	-0.02
	2A		-0.061	-0.02
	3A		-0.044	-0.01
	4A	V	-0.092	-0.03
	5A		-0.081	-0.03
	6A		-0.08	-0.03
BestSolv Sierra	13A	I	-0.044	-0.01
	14A		-0.09	-0.03
	15A		-0.031	-0.01
	16A	V	-0.026	-0.01
	17A		-0.105	-0.03
	18A		-0.101	-0.03
Fluoro IC	27	I	-0.001	0.00
	1B		-0.03	-0.01
	2B		-0.021	-0.01
	4B	V	-0.041	-0.01
	5B		-0.042	-0.01
	6B		-0.012	0.00
Opteon SF33	101	I	-0.05	-0.02
	102		-0.064	-0.02
	103		-0.04	-0.01
	104	V	-0.044	-0.01
	105		-0.034	-0.01
	106		-0.026	-0.01
AS-300	7A	I	0.06	0.02
	8A		0.02	0.01
	9A		-0.082	-0.03
	10A	V	-0.057	-0.02
	11A		-0.068	-0.02
	12A		-0.085	-0.03
Vertrel MCA	19	I	0.009	0.00
	20		-0.012	0.00
	21		0.03	0.01
	22	V	0.012	0.00
	23		-0.004	0.00
	24		-0.01	0.00
SF-30	7B	I	-0.02	-0.01
	8B		-0.028	-0.01
	9B		-0.034	-0.01
	10B	V	-0.068	-0.02

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	11B		-0.059	-0.02
	12B		-0.035	-0.01

Table 28. Inconel 718 MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	-0.05	-0.01
	2A		-0.02	0.00
	3A		-0.03	0.00
	4A	V	0	0.00
	5A		-0.02	0.00
	6A		-0.02	0.00
BestSolv Sierra	13A	I	-0.04	0.00
	14A		0	0.00
	15A		0	0.00
	16A	V	-0.02	0.00
	17A		-0.02	0.00
	18A		0	0.00
Fluoro IC	1B	I	0.03	0.00
	2B		0.04	0.00
	3B		-0.01	0.00
	4B	V	0	0.00
	5B		0	0.00
	6B		0	0.00
Opteon SF33	101	I	-0.03	0.00
	102		-0.02	0.00
	103		-0.02	0.00
	104	V	-0.02	0.00
	105		0.03	0.00
	106		-0.03	0.00
AS-300	7A	I	-0.07	-0.01
	8A		-0.06	-0.01
	9A		-0.09	-0.01
	10A	V	0.02	0.00
	11A		0.07	0.01
	12A		186.21	20.40
Vertrel MCA	19	I	0	0.00
	20		-0.02	0.00
	21		-0.01	0.00
	22	V	-0.04	0.00
	23		-0.07	-0.01
	24		-0.02	0.00
SF-30	7B	I	-0.06	-0.01
	8B		-0.01	0.00

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	9B		0.01	0.00
	10B	V	-0.02	0.00
	11B		-0.06	-0.01
	12B		-0.04	0.00

Table 29. Inconel 718 MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	0.1	0.01
	2A		0.08	0.01
	3A		0.03	0.00
	4A	V	0.05	0.01
	5A		0.1	0.01
	6A		0.08	0.01
BestSolv Sierra	13A	I	0.07	0.01
	14A		0.03	0.00
	15A		-0.15	-0.02
	16A	V	-0.01	0.00
	17A		0	0.00
	18A		0.09	0.01
Fluoro IC	1B	I	0.08	0.01
	2B		-0.01	0.00
	3B		-0.07	-0.01
	4B	V	0.05	0.01
	5B		-0.08	-0.01
	6B		-0.04	0.00
Opteon SF33	101	I	-0.08	-0.01
	102		-0.02	0.00
	103		0	0.00
	104	V	-0.04	0.00
	105		-0.02	0.00
	106		0	0.00
AS-300	7A	I	0.07	0.01
	8A		0.14	0.01
	9A		0	0.00
	10A	V	0.08	0.01
	11A		0.07	0.01
	12A		0.13	0.01
Vertrel MCA	19	I	0.08	0.01
	20		0.02	0.00
	21		0.09	0.01
	22	V	0.12	0.01
	23		0.04	0.00
	24		0.07	0.01
SF-30	7B	I	0.08	0.01
	8B		-0.14	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	9B		-0.04	0.00
	10B	V	0.16	0.02
	11B		-0.01	0.00
	12B		0.01	0.00

Table 30. Monel 400 MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	0.1	0.01
	2A		0.08	0.01
	3A		0.03	0.00
	4A	V	0.05	0.01
	5A		0.1	0.01
	6A		0.08	0.01
BestSolv Sierra	13A	I	0.07	0.01
	14A		0.03	0.00
	15A		-0.15	-0.02
	16A	V	-0.01	0.00
	17A		0	0.00
	18A		0.09	0.01
Fluoro IC	1B	I	0.08	0.01
	2B		-0.01	0.00
	3B		-0.07	-0.01
	4B	V	0.05	0.01
	5B		-0.08	-0.01
	6B		-0.04	0.00
Opteon SF33	101	I	-0.08	-0.01
	102		-0.02	0.00
	103		0	0.00
	104	V	-0.04	0.00
	105		-0.02	0.00
	106		0	0.00
AS-300	7A	I	0.07	0.01
	8A		0.14	0.01
	9A		0	0.00
	10A	V	0.08	0.01
	11A		0.07	0.01
	12A		0.13	0.01
Vertrel MCA	19	I	0.08	0.01
	20		0.02	0.00
	21		0.09	0.01
	22	V	0.12	0.01
	23		0.04	0.00
	24		0.07	0.01
SF-30	7B	I	0.08	0.01
	8B		-0.14	-0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	9B		-0.04	0.00
	10B	V	0.16	0.02
	11B		-0.01	0.00
	12B		0.01	0.00

Table 31. CDA 102 Copper MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1A	I	-0.29	-0.03
	2A		-0.29	-0.03
	3A		-0.21	-0.02
	4A	V	-0.12	-0.01
	5A		-0.18	-0.02
	6A		-0.1	-0.01
BestSolv Sierra	13A	I	-0.08	-0.01
	14A		-0.02	0.00
	15A		-0.04	0.00
	16A	V	-0.02	0.00
	17A		0.08	0.01
	18A		-0.09	-0.01
Fluoro IC	1B	I	-0.07	-0.01
	2B		-0.1	-0.01
	3B		-0.07	-0.01
	4B	V	-0.07	-0.01
	5B		-0.11	-0.01
	6B		-0.11	-0.01
Opteon SF33	101	I	-0.05	0.00
	102		-0.13	-0.01
	103		-0.11	-0.01
	104	V	-0.06	-0.01
	105		-0.33	-0.03
	106		-0.13	-0.01
AS-300	7A	I	-0.21	-0.02
	8A		-0.23	-0.02
	9A		-0.19	-0.02
	10A	V	0.01	0.00
	11A		-0.3	-0.03
	12A		-0.13	-0.01
Vertrel MCA	19	I	-0.13	-0.01
	20		-0.44	-0.04
	21		-0.1	-0.01
	22	V	-0.08	-0.01
	23		0.01	0.00
	24		-0.03	0.00
SF-30	7B	I	-0.06	-0.01
	8B		-0.02	0.00

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	9B		-0.11	-0.01
	10B	V	-0.01	0.00
	11B		-0.06	-0.01
	12B		-0.13	-0.01

Table 32. Eligiloy MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1	I	0.006	0.00
	2		-0.036	-0.02
	3		-0.03	-0.02
	4	V	0.001	0.00
	5		-0.002	0.00
	6		-0.002	0.00
BestSolv Sierra	13	I	0.018	0.01
	14		0.012	0.01
	15		0.02	0.01
	16	V	-0.005	0.00
	17		-0.012	-0.01
	18		-0.012	-0.01
Fluoro IC	19	I	-0.007	0.00
	20		0.002	0.00
	21		0	0.00
	22	V	-0.029	-0.02
	23		-0.022	-0.01
	24		-0.01	-0.01
Opteon SF33	46	I	-0.002	0.00
	47		-0.011	-0.01
	48		-0.008	0.00
	49	V	-0.009	-0.01
	50		-0.016	-0.01
	51		-0.007	0.00
AS-300	7	I	-0.21	-0.02
	8		-0.23	-0.02
	9		-0.19	-0.02
	10	V	0.01	0.00
	11		-0.3	-0.03
	12		-0.13	-0.01
Vertrel MCA	19	I	0.008	0.00
	20		0.008	0.00
	21		0.01	0.01
	22	V	-0.009	-0.01
	23		-0.033	-0.02
	24		-0.025	-0.01
SF-30	25	I	0.01	0.01
	26		0.022	0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	27		0.014	0.01
	28	V	-0.011	-0.01
	29		-0.013	-0.01
	30		-0.009	-0.01

Table 33. Titanium (Ti-6Al-4V) MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1	I	0.013	0.00
	2		-0.013	0.00
	3		-0.004	0.00
	4	V	-0.004	0.00
	5		-0.004	0.00
	6		-0.008	0.00
BestSolv Sierra	13	I	0.012	0.00
	14		0.013	0.00
	15		0.012	0.00
	16	V	-0.008	0.00
	17		-0.006	0.00
	18		-0.007	0.00
Fluoro IC	19	I	-0.004	0.00
	20		0.006	0.00
	21		-0.009	0.00
	22	V	-0.024	0.00
	23		-0.02	0.00
	24		-0.007	0.00
Opteon SF33	46	I	-0.009	0.00
	47		-0.01	0.00
	48		-0.003	0.00
	49	V	-0.006	0.00
	50		-0.004	0.00
	51		-0.006	0.00
AS-300	7	I	0.01	0.00
	8		0.006	0.00
	9		0.008	0.00
	10	V	-0.023	0.00
	11		-0.014	0.00
	12		-0.032	0.00
Vertrel MCA	19	I	0.001	0.00
	20		0.015	0.00
	21		0.009	0.00
	22	V	-0.024	0.00
	23		-0.013	0.00
	24		-0.026	0.00
SF-30	25	I	0.006	0.00
	26		-0.006	0.00

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	27		0.011	0.00
	28	V	-0.004	0.00
	29		-0.019	0.00
	30		-0.012	0.00

Table 34. Nitronic® 60 MPY Results

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
HFE-7100/Promosolv DR3	1	I	0.008	0.00
	2		0.014	0.01
	3		0.014	0.01
	4	V	0.016	0.01
	5		0.015	0.01
	6		0.017	0.01
BestSolv Sierra	13	I	-0.013	-0.01
	14		-0.018	-0.01
	15		-0.007	0.00
	16	V	-0.064	-0.04
	17		-0.014	-0.01
	18		0.044	0.02
Fluoro IC	19	I	-0.01	-0.01
	20		-0.007	0.00
	21		-0.006	0.00
	22	V	-0.005	0.00
	23		0.014	0.01
	24		0.003	0.00
Opteon SF33	46	I	0.005	0.00
	47		0.004	0.00
	48		0.002	0.00
	49	V	-0.002	0.00
	50		0.003	0.00
	51		-0.065	-0.04
AS-300	7	I	-0.001	0.00
	8		0.014	0.01
	9		0.007	0.00
	10	V	0.014	0.01
	11		-0.001	0.00
	12		0.007	0.00
Vertrel MCA	19	I	0.012	0.01
	20		0.009	0.00
	21		0.005	0.00
	22	V	0.005	0.00
	23		0.005	0.00
	24		-0.007	0.00
SF-30	25	I	0.038	0.02
	26		0.022	0.01

Solvent	Coupon #	Immersion (I) or Vapor (V) Exposure	Δ Mass (mg)	MPY (g/cm^2)
	27		0.009	0.00
	28	V	-0.008	0.00
	29		0.014	0.01
	30		0.01	0.01

Appendix B. Nonmetals Compatibility Results

Comprehensive nonmetals compatibility test results for mass, dimensional, hardness, maximum force, and elongation are presented for cleaning solvent candidates below. Results are presented with a color scheme of green (<1% change), yellow (≥1%, <10%), and red (≥10%) for each of the characteristics tested as use case for the soft good (e.g., dynamic or static application, etc.) should also be considered by end users when reviewing the data

Table 35. Buna N Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	0.44			-0.15			-0.25	5.36	8.54	4.94
BestSolv Sierra	-1.61	0.69		1.80	0.75		-3.13	-8.05	-11.04	-1.38
Fluoro IC	-2.39	-2.73	-0.19	-0.13			0.64	12.10	2.82	10.45
Opteon SF33	0.14			0.39			0.50	-1.02	-7.45	-8.14
AS-300	7.48	2.50	-1.50	39.73	6.52	0.76	0.93	3.95	-3.71	-1.62
Vertrel MCA	9.88	2.24	0.99	26.53	6.70	3.11	-1.80	-9.27	-16.41	-7.72
Opteon SF30	-104.64	-0.91		12.45	4.51	1.46	-0.66	-9.73	-14.36	-11.56

Table 36. EPDM Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	-0.03			0.41			0.06	5.90	16.25	3.56
BestSolv Sierra	0.15			0.34			0.15	-7.71	-7.50	-6.17
Fluoro IC	-1.42	-1.21	-0.18	0.09			2.05	3.23	1.39	-0.19
Opteon SF33	-2.24	3.86	-3.61	0.02	-0.08		0.45	11.27	5.14	4.08
AS-300	-3.42	-2.65	-1.08	1.01	-0.01		0.67	-2.83	-5.03	-3.70
Vertrel MCA	6.53	-1.89	-2.54	18.80	1.95	0.10	-0.28	-0.04	-4.94	-3.22
Opteon SF30	1.15	1.25	2.75	6.10	0.42		0.13	4.88	0.07	-0.17

Table 37. EPR Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	3.36	0.63		0.08			5.25	2.91	3.03	1.29
BestSolv Sierra	5.38	2.74	0.53	0.07			4.56	-4.13	-2.75	-3.68
Fluoro IC	5.37	2.69	0.42	0.06			6.05	-8.92	-6.23	-3.70
Opteon SF33	5.24	2.50	0.28	0.14			7.77	-7.27	-6.33	-4.48
AS-300	4.74	4.08	3.78	2.11	0.08		-8.85	-12.61	-13.42	-6.52
Vertrel MCA	8.52	4.38	1.49	10.20	2.61	-0.19	8.58	-3.64	-1.22	-1.28
Opteon SF30	1.93	3.93	3.60	15.39	0.30		6.05	-9.80	-8.39	-6.33

Table 38. FEP Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	3.22	2.14	2.92	0.01			-0.94	-0.64	0.15	1.25
BestSolv Sierra	3.16	1.97	2.79	0.01			-0.85	3.40	4.23	5.00
Fluoro IC	2.58	1.49	1.87	0.04			-0.85	-0.47	0.33	0.59
Opteon SF33	2.96	2.78	0.48	-0.01			-0.94	-3.73	-2.96	-2.43
AS-300	2.24	2.20	-0.23	0.01			-1.02	-0.68	0.12	1.33
Vertrel MCA	3.12	2.17	2.92	0.03			-0.77	-3.33	-2.56	-1.48
Opteon SF30	2.08	1.96	-0.40	0.02			-0.94	0.98	1.78	2.99

Table 39. FKM Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	2.73	0.86		4.81	3.34	2.37	1.94	-22.86	-31.50	-9.63
BestSolv Sierra	3.70	5.59	0.42	14.26	8.26	5.48	-0.71	-42.94	-52.36	-21.56
Fluoro IC	-0.76			0.38			4.78	-11.17	-14.15	0.37
Opteon SF33	4.93	4.37	1.39	8.76	4.98	3.39	-0.38	-25.44	-37.14	-3.90
AS-300	6.22	3.16	3.46	13.38	6.71	4.19	1.30	-27.30	-37.45	-7.56
Vertrel MCA	6.56	4.22	3.58	13.54	7.70	5.68	-4.26	-40.03	-50.82	-23.20
Opteon SF30	5.79	3.25	3.94	9.65	5.67	3.99	1.18	-27.91	-37.70	57.25

Table 40. FFKM Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	-0.38			27.42	14.67	8.76	25.67	-54.83	-63.35	-17.02
BestSolv Sierra	-0.39			0.58			33.21	-18.97	-30.98	-16.19
Fluoro IC	1.72	4.39	4.77	13.55	8.14	5.78	28.64	-31.20	-34.34	-6.16
Opteon SF33	0.27	-4.28		2.31	1.18	0.63	32.15	-17.50	-27.65	-13.39
AS-300	0.63			0.23			33.92	-26.88	-35.87	-16.92
Vertel MCA	4.67	2.47	1.53	30.86	8.92	5.89	27.01	-40.45	-50.72	-18.82
Opteon SF30	1.74	-0.42		2.15	1.19	0.66	34.06	-7.15	-17.74	-9.56

Table 41. Nylon Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	0.78			-0.07			-0.85	1.20	-0.61	32.15
BestSolv Sierra	1.19	-4.23	-0.86	0.05	-0.12		-1.06	-0.22	-3.71	23.81
Fluoro IC	1.56	-4.54	-1.69	0.07	-0.10		-1.94	5.61	6.93	33.86
Opteon SF33	0.21			0.08			-1.01	3.90	8.77	33.84
AS-300	0.56			0.21			-1.57	0.50	1.51	39.45
Vertrel MCA	1.01	0.89		0.00			-0.97	-3.62	-5.75	-6.63
Opteon SF30	2.15	1.68	1.30	0.15			-2.00	-2.14	-0.95	17.07

Table 42. PCTFE Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	3.89	2.36	3.00	-0.16			-1.01	-7.97	-10.14	-28.53
BestSolv Sierra	3.65	2.11	2.61	0.00			-0.08	-9.24	-11.38	-31.79
Fluoro IC	3.92	2.51	3.03	0.35			0.00	-4.36	-6.62	-13.41
Opteon SF33	2.36	2.18	-0.13	-0.35			0.00	-12.24	-14.31	-38.65
AS-300	2.12	2.15	-0.23	0.01			0.00	-11.66	-13.75	-23.79
Vertrel MCA	3.85	2.29	2.88	0.08			0.00	-6.06	-8.28	-14.35
Opteon SF30	2.82	2.42	0.17	0.04			-0.84	-5.51	-7.75	-14.11

Table 43. PEEK Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	-3.14	-1.12	-3.07	0.02			0.58	19.18	18.48	6.34
BestSolv Sierra	-0.61			0.02			-0.98	18.63	22.08	17.61
Fluoro IC	-0.90			0.02			-1.59	17.56	17.52	9.23
Opteon SF33	-3.68	-3.03	-4.64	0.03			-0.37	8.77	8.64	-7.17
AS-300	-1.33	-6.63	-0.93	0.03			1.19	0.64	-3.61	-14.13
Vertrel MCA	-1.28	-0.53		0.03			0.15	15.03	10.65	-8.72
Opteon SF30	-1.41	-6.62	-0.37	0.02			-0.46	17.40	17.88	3.77

Table 44. PTFE Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	0.77			0.15			-1.05	2.65	0.35	-2.30
BestSolv Sierra	0.81			0.04			-0.05	-2.18	-4.32	-13.71
Fluoro IC	0.85			0.08			0.15	0.38	-0.64	-7.46
Opteon SF33	2.09	3.10	-9.39	0.07			-0.26	-0.48	-1.78	-1.27
AS-300	0.73			0.04			-0.26	-0.03	-2.27	-3.26
Vertrel MCA	0.98			0.18			-0.12	1.57	-1.93	-2.87
Opteon SF30	2.10	1.57	2.78	0.09			0.51	-1.12	-2.43	-6.65

Table 45. PTFE with Silica Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	2.05	-1.06	1.13	0.77			-0.02	0.58	5.67	-6.18
BestSolv Sierra	1.38	-2.22	0.37	0.60			0.15	1.19	8.86	-2.06
Fluoro IC	2.02	-0.95		0.86			-0.02	3.35	8.03	-2.27
Opteon SF33	1.79	-2.01	0.77	0.60			-0.36	-1.07	6.17	-5.51
AS-300	2.09	-0.97		0.45			0.07	-0.18	12.78	-3.56
Vertrel MCA	1.82	-0.52		0.70			-0.27	2.64	7.42	0.06
Opteon SF30	4.12	2.30	3.60	0.50			0.07	2.47	11.29	-1.25

Table 46. Silicone Rubber Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	-2.19	2.51	-0.20	3.78	-0.24		-2.22	31.47	-4.75	-4.44
BestSolv Sierra	-5.07	1.25	-1.03	1.38	-0.10		0.00	17.26	-8.48	-3.38
Fluoro IC	-4.25	2.45	1.09	0.72			-4.44	38.37	-20.79	-5.71
Opteon SF33	-4.54	1.59	-1.98	1.61	-0.29		0.00	18.90	-14.23	-7.54
AS-300	-6.46	1.52	-0.72	3.26	-1.03	-1.01	1.67	-1.48	29.52	-4.02
Vertrel MCA	-4.42	1.93	-0.84	5.26	-0.89		-2.22	29.86	-12.00	-5.20
Opteon SF30	-6.21	0.62		0.87			-9.26	-29.92	5.29	-13.69

Table 47. Polyimide with Graphite Filler Compatibility Results

Solvent	Δ Thickness (%)			Δ Mass (%)			Δ Hardness (%)	Δ Max Force (%)	Δ Tensile Strength (%)	Δ Elongation (%)
	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure	0.5 hr Post-Exposure	24 hr Post-Exposure	168 hr Post-Exposure				
HFE-7100 / Promosolv	3.20	1.89	2.58	0.06			-0.42	4.48	4.48	-3.28
BestSolv Sierra	3.48	1.96	2.53	0.06			-0.34	2.16	2.16	-16.88
Fluoro IC	3.45	1.89	2.58	0.06			-0.17	-2.03	-2.03	-14.20
Opteon SF33	2.03	1.95	-0.16	0.06			-0.17	-4.12	-4.13	-9.21
AS-300	2.08	2.00	-0.21	0.12			-0.17	2.29	2.29	-1.40
Vertrel MCA	3.66	2.10	2.70	0.13			-0.17	2.35	2.35	-15.98
Opteon SF30	2.16	2.05	-0.06	0.11			-0.34	1.44	1.44	-4.96

Appendix C. WSTF Autoignition Temperature Results

Table 48. AIT Test Results for BestSolv Sierra (WSTF Report 25-48892)

Sample Number	Test Pressure		Sample Weight	AIT		Pressure at Ignition		Δ Temp Rise on Ignition		Δ Press Rise on Ignition		Heating Rate	
	MPa	(psia)	g	ºC	(ºF)	MPa	(psia)	ºC	(ºF)	MPa	(psia)	°C/min	(°F/min)
1	14	2000	0.229	253	487	25	3584	74	133	2	236	5.8	10.5
2			0.23	243	470	24	3461	99	178	1	206	5.2	9.4
3			0.23	253	487	25	3681	178	320	1	160	5.7	10.2
4			0.225	252	486	24	3508	143	257	1	74	5.1	9.2
5			0.23	243	470	17	2487	58	105	1	87	5.4	9.8
Average			0.2288	248.9	480.0	23.1	3344.2	110.3	198.6	1.1	152.6	5.5	9.8

Table 49. AIT Test Results for Ensolv Fluoro IC (WSTF Report 25-48893)

Sample Number	Test Pressure		Sample Weight	AIT		Pressure at Ignition		Δ Temp Rise on Ignition		Δ Press Rise on Ignition		Heating Rate	
	MPa	(psia)	g	ºC	(ºF)	MPa	(psia)	ºC	(ºF)	MPa	(psia)	°C/min	(°F/min)
1	14	2000	0.5	399	751	29	4231	407	732	1	203	4.7	8.5
2			0.51	398	749	30	4364	439	791	1	192	4.8	8.7
3			0.53	402	756	21	3118	445	801	1	137	4.9	8.8
4			0.529	404	760	22	3195	347	625	1	163	5.3	9.5
5			0.53	401	754	32	4616	92	165	2	328	5.1	9.2
Average			0.5198	401.1	754.0	26.9	3904.8	346.0	622.8	1.4	204.6	5.0	8.9

Table 50. AIT Test Results for Opteon SF33 (WSTF Report 25-48891)

Sample Number	Test Pressure		Sample Weight	AIT		Pressure at Ignition		Δ Temp Rise on Ignition		Δ Press Rise on Ignition		Heating Rate	
	MPa	(psia)	g	ºC	(ºF)	MPa	(psia)	ºC	(ºF)	MPa	(psia)	°C/min	(°F/min)
1	14	2000	0.227	276	528	27	3881	52	94	1	103	5.0	9.0
2			0.23	275	527	27	3883	39	70	1	106	5.3	9.6
3			0.229	270	518	26	3753	51	92	1	214	5.2	9.3
4			0.23	260	500	25	3611	71	128	3	450	5.0	9.0
5			0.229	272	522	24	3517	54	97	2	227	4.8	8.6
Average			0.229	270.6	519.0	25.7	3729.0	53.4	96.2	1.5	220.0	5.1	9.1

Table 51. AIT Test Results for Amolea AS-300 (WSTF Report 25-48889)

Sample Number	Test Pressure		Sample Weight	AIT		Pressure at Ignition		Δ Temp Rise on Ignition		Δ Press Rise on Ignition		Heating Rate	
	MPa	(psia)	g	ºC	(ºF)	MPa	(psia)	ºC	(ºF)	MPa	(psia)	°C/min	(°F/min)
1	14	2000	0.219	157	314	22	3189	691	1244	13	1953	4	7.0
2			0.218	163	326	21	3091	326	586	14	1977	5.6	10.0
3			0.23	156	312	21	3084	262	471	13	1954	3.9	7.0
4			0.224	166	330	22	3172	747	1344	16	2379	5.6	10.0
5			0.225	151	304	21	2985	136	245	12	1704	4.4	7.9
Average			0.2232	158.4	317.2	21.4	3104.2	432.2	778.0	13.7	1993.4	4.7	8.4

Table 52. AIT Test Results for Vertrel MCA (WSTF Report 25-48954)

Sample Number	Test Pressure		Sample Weight	AIT		Pressure at Ignition		Δ Temp Rise on Ignition		Δ Press Rise on Ignition		Heating Rate	
	MPa	(psia)	G	°C	(°F)	MPa	(psia)	°C	(°F)	MPa	(psia)	°C/min	(°F/min)
1	14	2000	0.5	152	305	21	2980	63	113	2	302	5.2	9.4
2			0.51	155	311	19	2826	44	79	1	203	5.8	10.4
3			0.53	161	321	17	2419	22	39	1	136	5.0	9.0
4			0.529	138	281	19	2734	32	58	2	259	5.6	10.0
5			0.53	153	307	18	2656	68	123	1	123	5.0	9.0
Average			0.5198	151.7	305.0	18.8	2723.0	45.8	82.4	1.4	204.6	5.3	9.6

Table 53. AIT Test Results for Opteon SF30 (WSTF Report 25-48890)

Sample Number	Test Pressure		Sample Weight	AIT		Pressure at Ignition		Δ Temp Rise on Ignition		Δ Press Rise on Ignition		Heating Rate	
	MPa	(psia)	G	°C	(°F)	MPa	(psia)	°C	(°F)	MPa	(psia)	°C/min	(°F/min)
1	14	2000	0.23	158	316	22	3119	38	68	2	224	5.2	9.4
2			0.229	148	299	20	2916	64	116	2	270	5.8	10.5
3			0.23	150	302	21	2982	43	78	3	408	5.2	9.3
4			0.228	156	313	21	2984	42	76	3	370	5.6	10.1
5			0.23	133	271	20	2909	60	108	6	938	5.0	9.0
Average			0.2294	149.0	300.2	20.6	2982.0	49.6	89.2	3.0	442.0	5.4	9.7