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# Filtration of Spaceflight Propulsion and Pressurant Systems

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April 2022

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April 2022

## Acknowledgments

The assessment team would like to thank Art Casillas, Chuck Pierce, David Eddleman, Steve Gentz, Don Parker, Bill Sadowski, and Mark Terrone for reviewing this report.

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# NASA Engineering and Safety Center
# Technical Assessment Report

# Filtration of Spaceflight Propulsion and Pressurant Systems

**February 17, 2022**

Restrictive Markings Revised March 2, 2023

# Report Approval and Revision History

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| | NESC Director | Date |

| Version | Description of Revision | Office of Primary Responsibility | Effective Date |
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# Technical Assessment Report

## 1.0 Notification and Authorization

NASA has provided little guidance for determining and implementing appropriate filtration of spaceflight propulsion and pressurant systems. Additionally, industry standards typically used for building and verifying filter performance are antiquated and lack applicability to propulsion systems. The NASA Engineering and Safety Center (NESC) has been requested to perform a gap analysis, identify risks, and develop a mitigation plan for spaceflight propulsion filtration.

Key stakeholders for this assessment include the NASA Office of the Chief Engineer (OCE) and all NASA flight and ground programs.

## 2.0 Signature Page

Submitted by:

*Team Digital Signature on File*

| | |
|---|---|
| Dr. Daniel J. Dorney | Date |

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| Mr. Patrick A. Simpkins | Date | Ms. Alejandra Constante Perez | Date |

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.

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## 3.1 Acknowledgments

The assessment team would also like to thank Art Casillas, Chuck Pierce, David Eddleman, Steve Gentz, Don Parker, Bill Sadowski, and Mark Terrone for reviewing this report.

# 4.0 Executive Summary

Contamination has been accepted as the root cause of many anomalies in spaceflight systems. However, some of these anomalies could have been prevented if an appropriate filtration approach had been specified and implemented. No standards exist for sizing, building, and verifying the performance of spaceflight propulsion/pressurant filters. Component and system cleanliness standards exist, but the interpretation of cleanliness level applicability varies widely. There is no standard technique to determine how cleanliness levels are applied at a system level and how they correlate to filtration requirements.

Basic filtration terms, such as “nominal” and “absolute” filter ratings, have different meanings from vendor to vendor. This assessment was undertaken to define a common approach to filtration terminology, suggested guidelines, design, and verification for spaceflight propulsion and pressurant systems. Guidance for the design of a filter element, such as filtration rating, contamination capacity, flow rate vs. pressure drop, and differential collapse pressure, was evaluated, along with filter housing performance (i.e., proof and burst). Verification of the existing requirements is intended to address issues such as the limited applicability of bubble point testing for filtration ratings and the lack of test options.

This assessment represents the first step in a multi-step process. The focus here is on filtration terminology, requirements, design, and verification. Future efforts will need to address system-level issues, cleaning processes, and manufacturing. The current assessment assumed foreign object debris, domestic object debris, and/or contaminants already exist in a system. It was not intended to address the sources of debris and contaminants.

Section 8 provides process guidance on establishing appropriate cleanliness requirements and verifying capabilities. Use of this approach is recommended for all launch vehicle and spacecraft propulsion systems. While the contamination control solution for each program will vary, this common approach will provide the necessary means for consistent assessments. Section 9 provides guidance on the collection and measurement of samples for determining cleanliness.

Section 10 presents the findings, observations, and NESC recommendations developed as part of this assessment. The major findings include:

- The basic parameters that impact the design of a filtration system are:
  - The largest tolerable particle for each component or assembly within the propulsion or pressurant system.
  - The maximum pressure drop allocated for the system.
  - The volume/mass available in the system.
  - The amount and type of potential contaminant that may be encountered throughout the service life.
- Historically, filtration system design has not included the contributions of all relevant sources.
- A system made up of components cleaned to level 100 may not result in a level 100 clean system, due to the cumulative nature of contamination.
- Many filters are inadequately sized for the components and/or systems they are designed to protect.
- Qualification and acceptance testing are not always performed for the filters used to mitigate hazards in spaceflight programs.

- Ground support system filters often receive less testing and analysis than vehicle filters.
- Sizing guidelines for filters are applicable to foreign object debris (FOD) screens and can be used as part of a FOD screen assessment.
- A range of acceptable micron ratings in the filter design specification (i.e., maximum and minimum micron ratings) ensures proper margins.
- This filtration sizing process, its identified gaps, and its challenges may be applicable to a range of systems beyond propulsion.
- Contaminant Control Plan guidance historically included requirements to determine the contamination generation profile of components when purchased. However, recent guidance has omitted this direction.
- There is no evidence that the IEST-STD-CC1246E requirement for 95% confidence limits on contamination samples to verify cleanliness level has ever been implemented.

NESC recommendations were generated from the findings and observations, and are directed to the NASA OCE, unless otherwise specified:

- Requirements documents for fluid systems should include predicted contamination generation and sensitivity characteristics.
- Filter specifications should include flow and pressure differential requirements for a clean filter and a filter at the specified holding capacity (directed to OCE and flight programs).
- System cleanliness should be an assessment of the entire system, including internal and external contributors, ground support systems, and media cleanliness levels (directed to OCE and flight programs).
- A system’s filtration requirements should be based on the contaminant sensitivity of its operating components.
- All filter performance should be verified through qualification and acceptance testing (directed to OCE and flight programs).
- Ground support system filters should receive the same testing and analysis as vehicle filters (directed to OCE and ground support programs).
- The effects of acceleration on the settling/unsettling and filtering of particulates in the system should be considered during the design of filtration systems (directed to OCE and flight programs).
- Updated contamination profiles and ISO test dust standards should be developed and correlated to test data.
- The processes and guidelines developed in this effort should be assessed for applicability to spacecraft closed-loop and air revitalization systems (directed to OCE and flight programs).
- Size, quantity, and type of particulate matter generated by a component under life cycle operating conditions and as a result of post-fluid exposure should be recorded as part of verification activities (directed to OCE and flight programs).
- Implement the contamination sampling process outlined in Table 9-1 of this report in lieu of the IEST-STD-CC1246E requirement for 95% confidence limits.

# 5.0 Scope and Assessment Plan

Contamination and contamination control are typically addressed in NASA programs via NASA-STD-6016 [ref. 1]. In turn, NASA-STD-6016 requires the generation of a Contamination Control Plan in accordance with ASTM E1548 [ref. 2]. ASTM E1548 Contamination Control Plan guidance further distinguishes between the various types of contaminants. The scope of this effort is bound within the "Particulate" assessment, as identified in ASTM E1548. Therefore, this effort does not seek to initiate new requirements but is intended to clarify existing requirements.

The scope of this assessment and how it fits within a NASA program is shown in Figure 5-1 and Figure 5-2.Figure 5-1

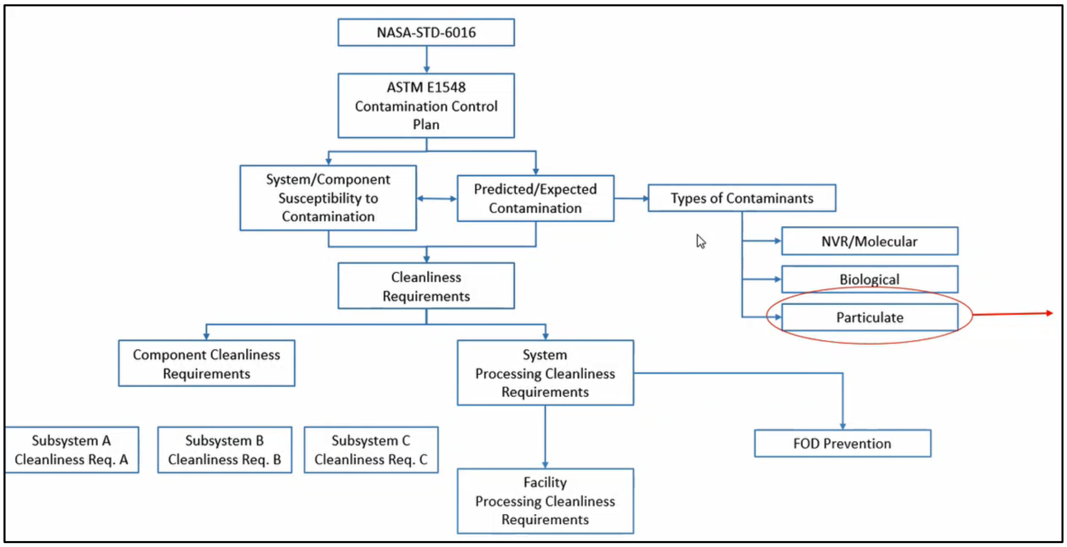
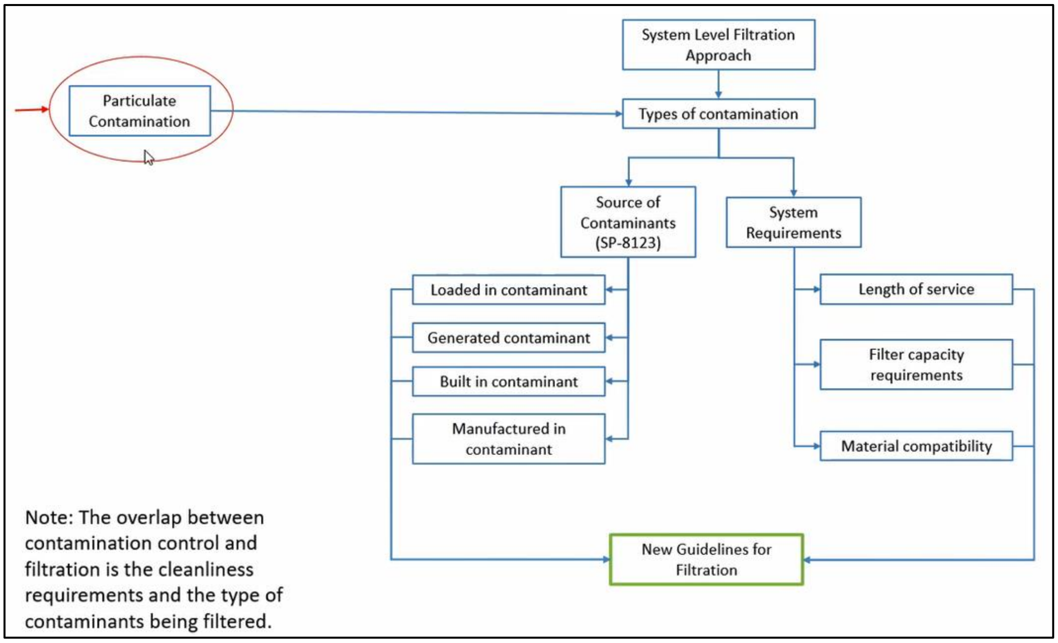


*Figure 5-1. Contamination and Cleanliness Scope*



Note: The overlap between contamination control and filtration is the cleanliness requirements and the type of contaminants being filtered.

*Figure 5-2. Filtration Guidelines Scope*

Technical activities for this assessment included:

- Assessing existing filtration standards and guidance documents for propellant and pressurant systems.
- Surveying vendors to better understand their concerns about filtration systems.
- Developing guidelines for system filtration design and implementation.
- Identifying key variables for guidelines.
- Determining applicability of the proposed methods to other systems.
- Determining the need for follow-on testing and analyses.
- Documenting findings, observations, and NESC recommendations in a final report.

The NESC assessment team was divided into three sub-teams, corresponding to the three basic steps of the filtration assessment process:

1. **Team 1: Determine the system contamination profile** – The contamination profile is the amount and size distribution of contaminant particles expected throughout the life of the system.
2. **Team 2: Identify system filtration guidelines and best practices** – The system filtration requirements define the specific portion of the contamination profile that needs to be filtered/removed.
3. **Team 3**: **Specify performance requirements/design/verification for filter(s)** – These are the component (i.e., filter) level requirements that will determine what requirements should be flowed to the filter design, how they should be verified, and what specific design requirements should be.

## 6.0 Background and Problem Description

Contamination and contamination-related anomalies have plagued spaceflight systems since the Apollo program. As a result, cleanliness standards have been developed, with the primary focus on individual components and cleanrooms (e.g., MIL-STD-1246, [ref. 3]) There remains a disconnect as to how these requirements should be interpreted and implemented at a system level.

It has been left to individual projects to determine implementation of filtration requirements. An unintended result is that contamination has been accepted as a root cause of failures in all modern spaceflight systems. The most comprehensive set of data comes from the Shuttle program and its Problem Reporting Analysis and Corrective Action (PRACA) database [ref. 4]. A basic search of the PRACA database returns more than 50,000 hits on contamination, FOD, filter, and cleanliness. Many of these issues were violations of the requirements in reference 60, which addresses cleanliness but not filtration. This underscores the importance of filtration system implementation.

It has been common practice for NASA programs to use MIL-STD-1246 as the cleanliness standard and to formulate a Contamination Control Plan via NASA-STD-6016 and ASTM E1548, but the frequency of contamination issues indicates a gap still exists.

## 6.1 Cleanliness Requirements

### 6.1.1. MIL-STD-1246

MIL-STD-1246 was originally released in the 1960s and underwent several revisions before the Contamination Control Division of the Institute of Environmental Sciences and Technology (IEST) was tasked with maintaining the document. In doing so, MIL-STD-1246 has been replaced by IEST-STD-CC1246 [ref. 5] and become the industry standard.

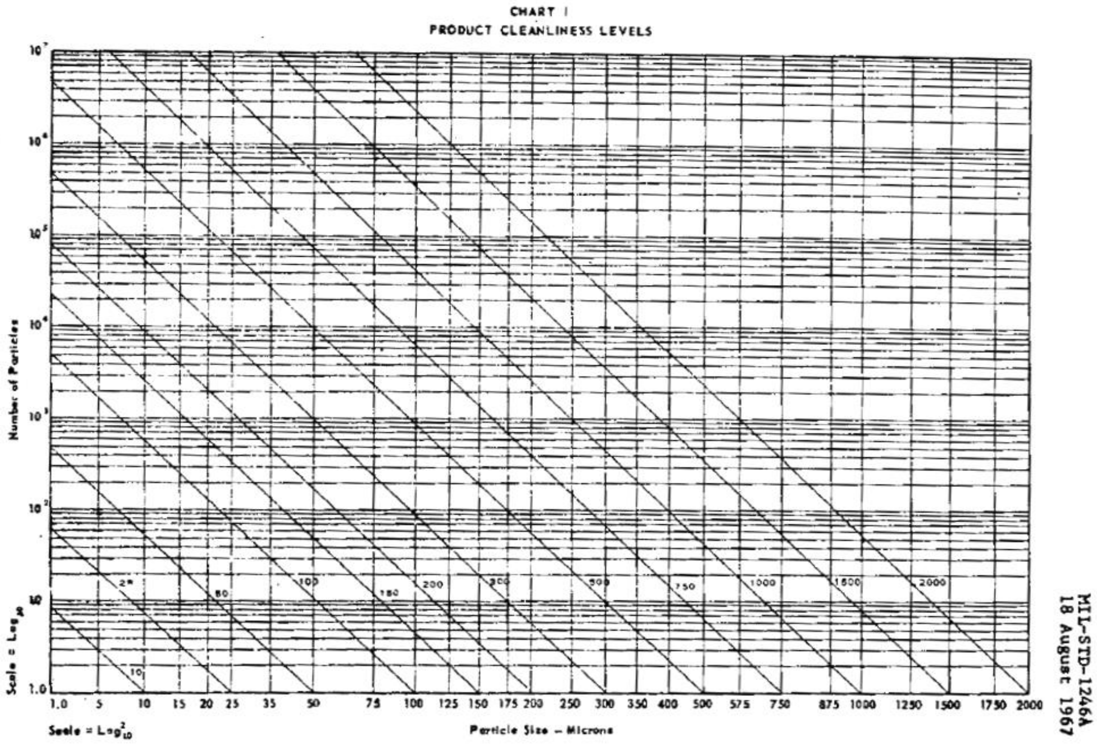
The original document[1], MIL-STD-1246A, used a particle distribution per the following $\log^2$-log equation.

$$LogN = 0.9260(Log^2X_1 - Log^2X)$$

Where:

- $N$ is the number of particles
- .9260 is the tangent of the angle
- $X$ is the particle size
- $X_1$ is the cleanliness level

The resulting distribution is shown in Figure .



Research shows that naturally occurring particulate contamination follows a log-normal distribution with a geometric mean of near one (1) micron particle. This distribution follows a straight line when plotted on a log x $\log^2$ scale graph. The grid is derived from the log-normal ‹ · Gaussian distribution function which provides a close fit to real contamination data. The lines on the chart represent the maximum contamination permitted for each level and the plot point is the number of particles above given size versus particle size. The curves can be expressed as log n = 0.9260 ($Log^2X_1$ - $Log^2X$), where n is the number of particles, 0.9260 is the tangent of the angle, X is the particle size, and $X_1$ is the cleanliness level.

*Figure 6-1. Particle Size Distribution*

---

[1] MIL-STD-1246(MI) could not be found

The origin of this distribution is not known, but the caption indicates it is based on “naturally occurring particulate contamination.” The full caption text states:

> “Research shows that naturally occurring particulate contamination follows a log-normal distribution with a geometric mean of near one (1) micron particle. This distribution follows a straight line when plotted on a log x $\log^2$ scale graph. The graph is derived from the log-normal Gaussian distribution function, which provides a close fit to real contamination data. The lines on the chart represent the maximum contamination permitted for each level, and the plot point is the number of particles above a given size vs. particle size. The curves can be expressed as $\log n = 0.926\ (\mathrm{Log}^2 X_1 - \mathrm{Log}^2 X)$, where n is the number of particles, 0.926 is the tangent of the angle, X is the particle size, and $X_1$ is the cleanliness level.”

As MIL-STD-1246 has been revised, there have been slight adjustments to the cleanliness levels, such as using actual values rather than rounded values and conversions for metric and English units. But essentially, the original particle size distribution is being used today. A notable exception is revision “E,” which states, “Alternate slopes may be used but must be designated after the cleanliness level.” However, it is unclear if this has been followed.

There has been discussion as to the applicability of using “naturally occurring particulate contamination” distribution curves for internal cleanliness of propulsion systems and propulsion media. For the purposes of filter sizing, the relationship of the specified particle size distribution curve to the particle size distribution curve was determined to be less relevant than the relationship of the specified particle size distribution curve to the particle size distribution curve *of the test dust*. Particle counts of the former standard, AC Coarse Test Dust (ACCTD), showed a good correlation to the MIL-STD-1246 level 100 (Figure 6-2). ACCTD is no longer available and has been replaced with other test dusts, per ISO 12103. However, no comparative counts exist for these dusts.

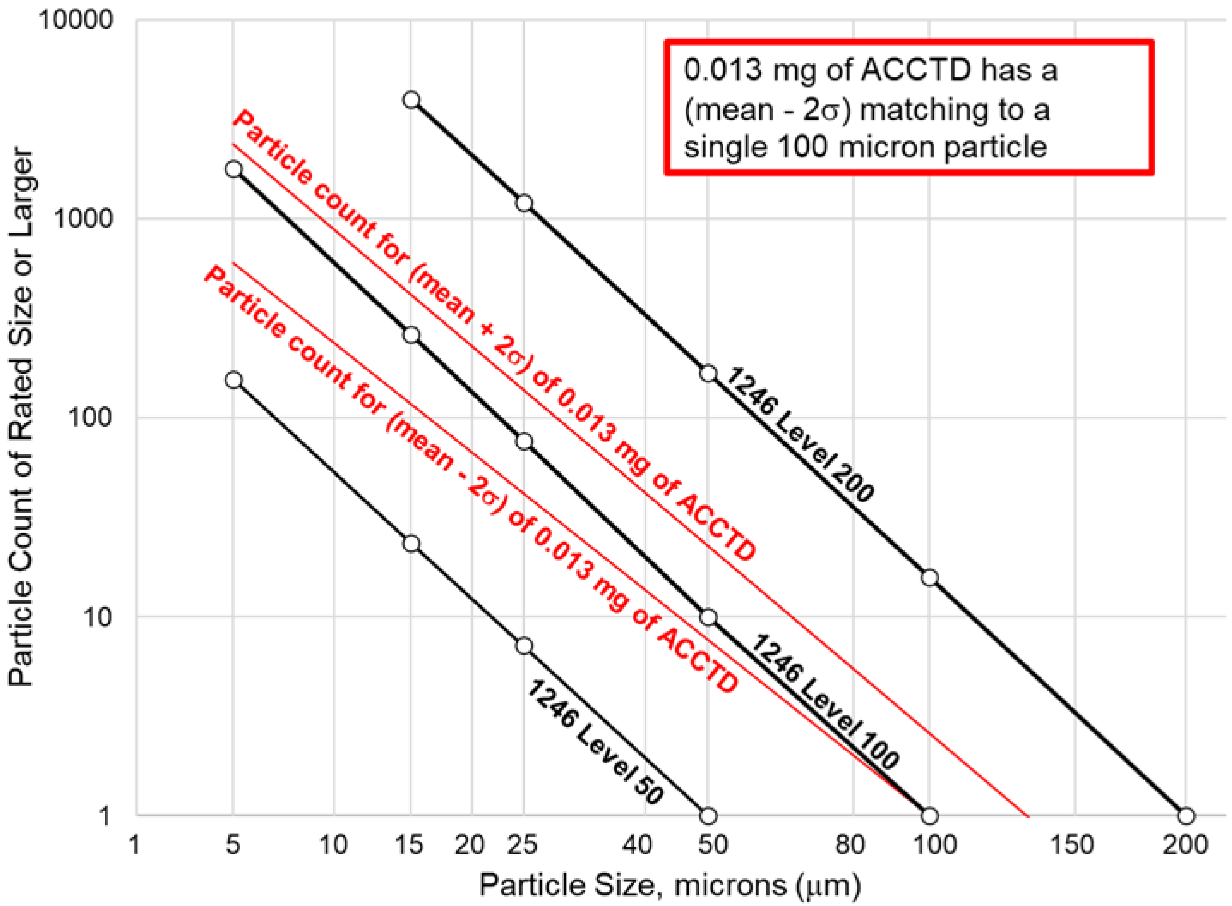
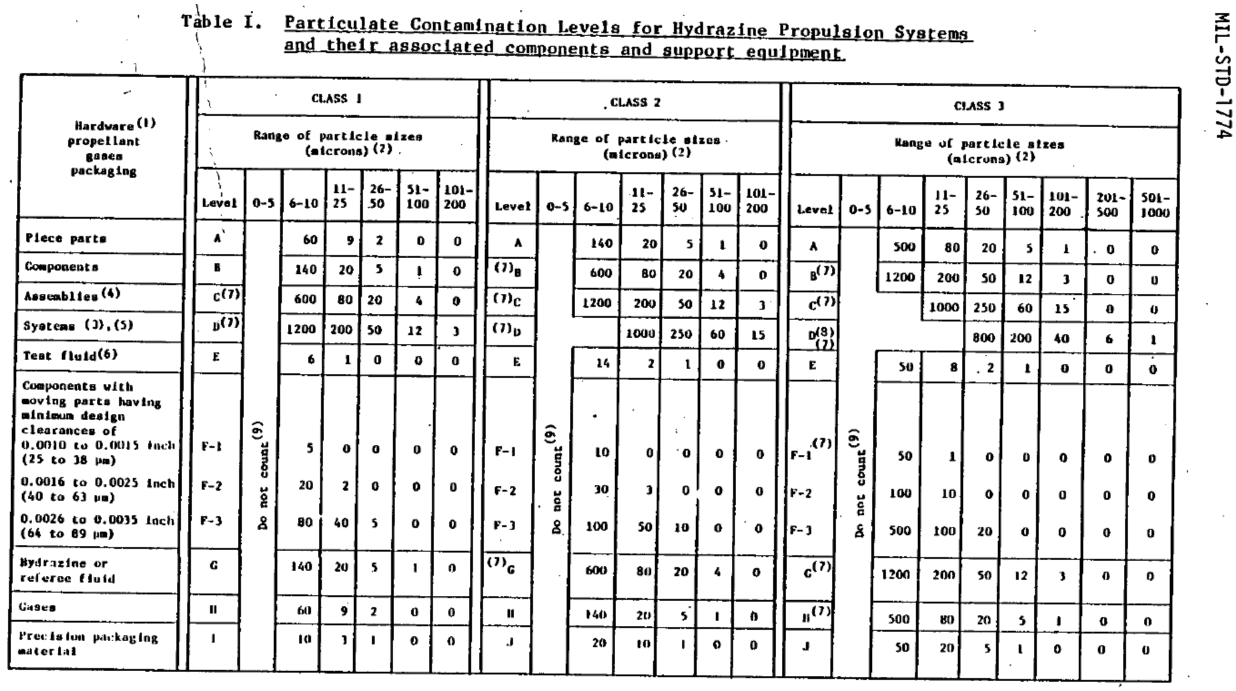


*Figure 6-2. ACCTD Particle Count Distribution Compared to MIL-STD-1246 Cleanliness Levels*

### 6.1.2. MIL-STD-1774 (Canceled Document)

MIL-STD-1774, “Process for Cleaning Hydrazine Systems and Components,” was released in 1982. This document established cleanliness level requirements as well as cleaning procedures, packaging, and documentation for the procurement of hydrazine systems. The cleanliness levels specified in MIL-STD-1774 were more stringent than those of MIL-STD-1246, with “flatter” particle size distribution curves that predicted fewer small-sized particles (see Figure 6-3). The source of these levels is not known, but the levels appear to coincide with those used in the AIAA paper for filter sizing [ref. 6].



MIL-STD-1774

Table I. Particulate Contamination Levels for Hydrazine Propulsion Systems and their associated components and support equipment

| Hardware(1) propellant gases packaging | CLASS 1 | | | | | | | CLASS 2 | | | | | | | CLASS 3 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Range of particle sizes (microns) (2) | | | | | | | Range of particle sizes (microns) (2) | | | | | | | Range of particle sizes (microns) (2) | | | | | | | | |
| | Level | 0-5 | 6-10 | 11-25 | 26-50 | 51-100 | 101-200 | Level | 0-5 | 6-10 | 11-25 | 26-50 | 51-100 | 101-200 | Level | 0-5 | 6-10 | 11-25 | 26-50 | 51-100 | 101-200 | 201-500 | 501-1000 |
| Piece parts | A | Do not count(9) | 60 | 9 | 2 | 0 | 0 | A | Do not count(9) | 140 | 20 | 5 | 1 | 0 | A | Do not count(9) | 500 | 80 | 20 | 5 | 1 | 0 | 0 |
| Components | B | | 140 | 20 | 5 | 1 | 0 | (7)B | | 600 | 80 | 20 | 4 | 0 | B(7) | | 1200 | 200 | 50 | 12 | 3 | 0 | 0 |
| Assemblies (4) | C(7) | | 600 | 80 | 20 | 4 | 0 | (7)C | | 1200 | 200 | 50 | 12 | 3 | C(7) | | | 1000 | 250 | 60 | 15 | 0 | 0 |
| Systems (3),(5) | D(7) | | 1200 | 200 | 50 | 12 | 3 | (7)D | | | 1000 | 250 | 60 | 15 | D(8)(7) | | | | 800 | 200 | 40 | 6 | 1 |
| Test fluid(6) | E | | 6 | 1 | 0 | 0 | 0 | E | | 14 | 2 | 1 | 0 | 0 | E | | 50 | 8 | 2 | 1 | 0 | 0 | 0 |
| Components with moving parts having minimum design clearances of 0.0010 to 0.0015 inch (25 to 38 μm) | F-1 | | 5 | 0 | 0 | 0 | 0 | F-1 | | 10 | 0 | 0 | 0 | 0 | F-1(7) | | 50 | 1 | 0 | 0 | 0 | 0 | 0 |
| 0.0016 to 0.0025 inch (40 to 63 μm) | F-2 | | 20 | 2 | 0 | 0 | 0 | F-2 | | 30 | 3 | 0 | 0 | 0 | F-2 | | 100 | 10 | 0 | 0 | 0 | 0 | 0 |
| 0.0026 to 0.0035 inch (64 to 89 μm) | F-3 | | 80 | 40 | 5 | 0 | 0 | F-3 | | 100 | 50 | 10 | 0 | 0 | F-3 | | 500 | 100 | 20 | 0 | 0 | 0 | 0 |
| Hydrazine or referee fluid | G | | 140 | 20 | 5 | 1 | 0 | (7)G | | 600 | 80 | 20 | 4 | 0 | G(7) | | 1200 | 200 | 50 | 12 | 3 | 0 | 0 |
| Gases | H | | 60 | 9 | 2 | 0 | 0 | H | | 140 | 20 | 5 | 1 | 0 | H(7) | | 500 | 80 | 20 | 5 | 1 | 0 | 0 |
| Precision packaging material | I | | 10 | 3 | 1 | 0 | 0 | J | | 20 | 10 | 1 | 0 | 0 | J | | 50 | 20 | 5 | 1 | 0 | 0 | 0 |

*Figure 6-3. Cleanliness Levels from MIL-STD-1774*

It is not known why this standard was canceled without replacement in 1995. However, it should be noted that ECSS-E-35-06C, "Cleanliness Requirements for Spacecraft Propulsion Hardware," written in 2008, appears to be based on MIL-STD-1774 and is in use by the European Space Agency [ref. 7].

## 6.2 Verification of Requirements

In determining the critical particle size for a given orifice, the "three-ball method" is typically used. This method assumes three spherical contaminants gather at the orifice to cause a blockage. In general, the critical sphere size would be 46.41% of the orifice diameter (see Figure 6-4). However, typical contamination particles have been determined to have an average aspect ratio between 0.6 and 0.7 [ref. 6]. As the aspect ratio decreases from a sphere, the critical particle size increases and approaches 50% of the orifice diameter. Given the uncertainty of contamination particle shapes, a simple factor of ½ is a good approximation for the critical particle size of a given orifice.

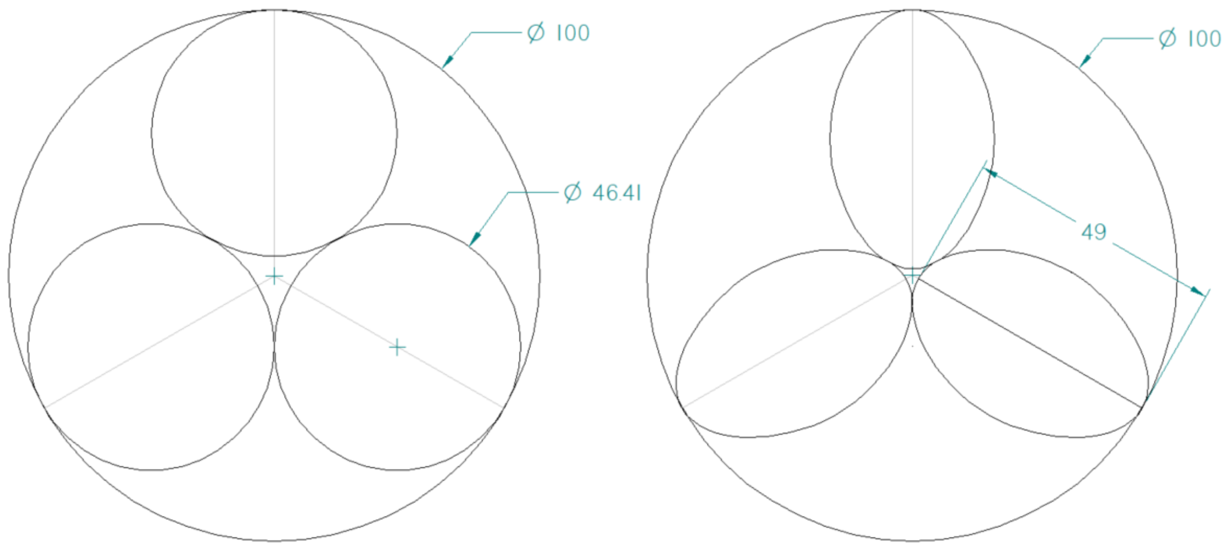


*Figure 6-4. Critical Particle Size for Spherical Contaminants and Contaminants with Lower Aspect Ratio*

## 6.3 Application of Requirements

NASA has not provided a standard nor recommended a method to determine the appropriate filtration for propulsion or pressurant systems (or other similar systems). Component/system cleanliness standards exist, but the interpretation of cleanliness level applicability varies widely. There is no standard method to determine how cleanliness levels are applied at a system level and how they correlate to filtration requirements. Current cleanliness specifications are based on a legacy log-log particle size distribution equation and do not represent actual particle size distributions found in spaceflight components and systems [e.g., refs. 3, 5]. This makes it impossible to accurately assess filtration adequacy or margin and provide optimized filtration system designs. The standard referee test medium has a different particle size distribution than that specified in the cleanliness requirements. The test medium is based on the particle size distribution of sand found in the Arizona desert [ref. 13]. This approach was practical for air filter testing when it was developed in the 1950s, but has little relevance to modern spaceflight systems.

The standard for filter pore size verification testing is most applicable to a filter design that uses a specific wire mesh weave. The verification method required by this standard has questionable applicability to the spaceflight filter designs used today and in some cases is not physically possible, but no alternate test method exists.

# 7.0 Development of Filtration Guidelines

## 7.1 System Boundary

A methodology to evaluate contaminants for a system is to create a system boundary around the portion of the system that is being evaluated (Figure 7-1). This method is useful for designing systems and serves as a starting point for anomaly investigations. Consider that contaminants can enter the controlled area in only one of four ways:

1. Loaded with the fluid or gaseous media.
   - The only type of contamination actively crossing the system boundary. Controlled by the system interface control document (ICD) and media specifications.
2. Built into parts and components at the vendor.
   - This type of contamination is controlled by component specifications.
3. Introduced by manufacturing processes, such as welding and cutting at the sub-assembly and final assembly levels.
   - This type of contamination relies primarily on process controls and may be the most difficult to bound.
4. Self-generated by moving parts and soft-good degradation within the system.
   - This type of contamination is controlled by the component specifications.

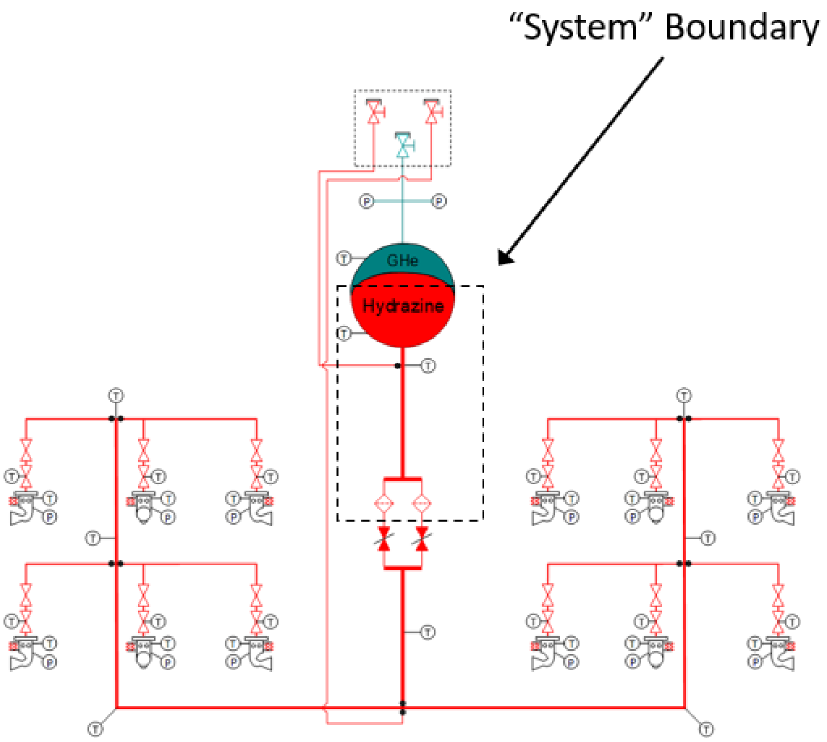


*Figure 7-1. System Boundary Example*

Figure 7-2 shows the basics of filtration guidelines that will be used to address contamination.

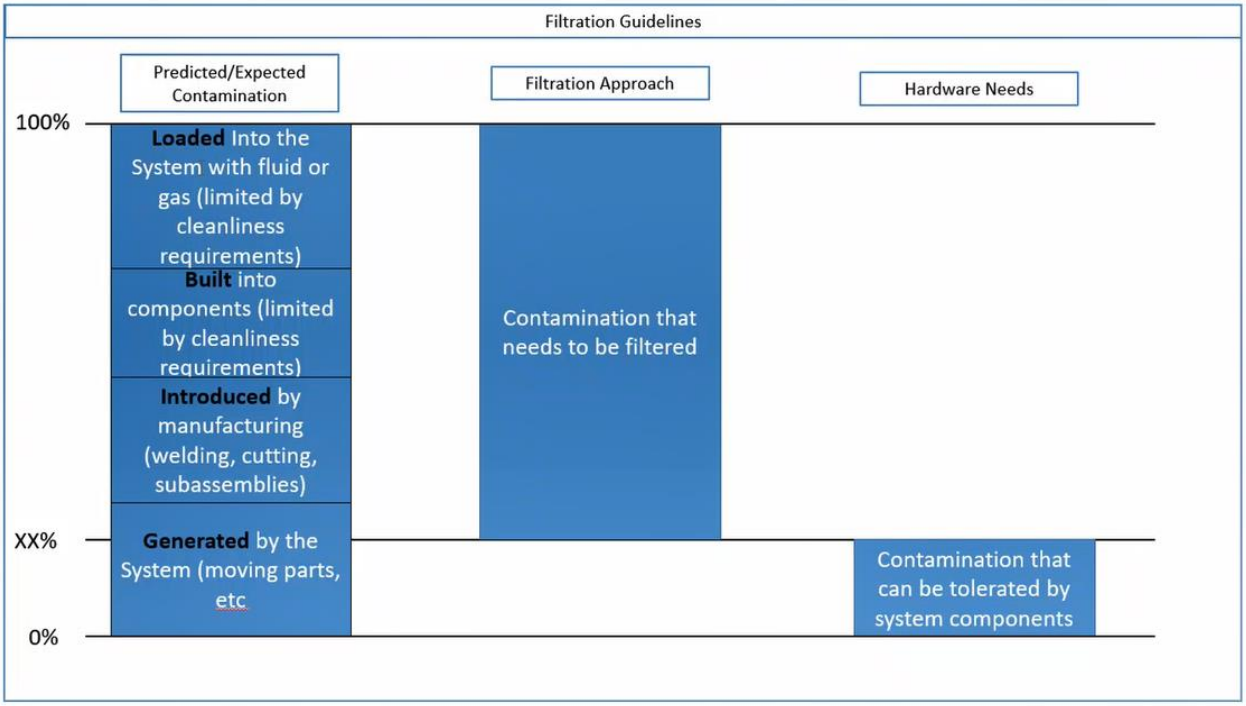


*Figure 7-2. Filtration Guidelines*

## 7.2 Literature Review of Existing Standards and Heritage Documents

The NESC assessment team evaluated an extensive cross-section of standards, guidelines, and other filtration-related documents during this study. While many are cited in the References (Section 17.0), Appendix A contains the complete list of documents. While the primary document review results are discussed in the main body of the report, Appendix A also contains additional comments for select documents.

## 7.3 Filtration and Contamination Terminology

One outcome of the literature survey was the recognized need for a common set of filtration and contamination-related terminology. Therefore, to aid in subsequent discussions, the NESC assessment team agreed on definitions for a number of commonly used terms (see Appendix B).

## 7.4 Vendor Survey

A survey was sent to filtration system vendors/users across the aerospace industry and in NASA flight programs. The intent of the survey was to identify filtration issues of interest. The survey was composed of five questions:

1. What type of flight systems do you utilize that require system filtration, and/or what type of filtration components do you develop?
2. What are your greatest concerns and challenges with system filtration and/or filtration hardware?
3. What methods/guidelines do you currently use for system filtration and/or filtration components?
4. Are there any lessons learned that can be shared?

5. Is there any other system filtration or filtration hardware information that may be relevant to our assessment?

Fifteen responses were received from the 28 vendors/users/programs contacted. The responses were thoroughly scrubbed and generalized to protect vendor proprietary data. The responses correlate well with the themes and gaps discussed in this report. The scrubbed survey results were partially redacted from Appendix C in this revision but are available in Version 1.1 of this report.

## 7.5 Heritage Lessons Learned

The NESC assessment team subject matter experts were asked to provide filtration lessons learned from previous programs. The lessons learned supported the assessment discussions and are provided in Appendix D.

# 8.0 Process Guidelines

This section presents a step-by-step process (noting where gaps exist) that can be used to determine appropriate filtration for a system. It identifies additional considerations for the user to take into account. This section is intended to be a standalone set of guidelines. A flow diagram of the filtration design process outlined in Section 8 is shown in Appendix E. The step-by-step process for filtration system design can be found in Appendix F. A detailed example illustrating the process described in Section 8 and Appendix E can also be found in Appendix G.

There are three basic steps to assessing the filtration needs for a system:

1. Determine the contamination[2] profile.
2. Identify the filtration needs.
3. Specify an appropriate filter.

## 8.1 Determine the Contamination Profile for the System

The first step in determining the filtration needs for a system is to determine the contamination that is *expected* in that system[3] (i.e., the contamination allowed in the system based on the relevant requirements.) Section 8.1 provides details of the process that system designers can use to assess the contamination profile of their system and calculate the filtration needed in terms of holding capacity. There are four possible methods by which contamination may be introduced that must be considered:

1. Contamination that is built into components.
2. Contamination that is introduced during system assembly.
3. Contamination that is loaded into the system with media.[4]
4. Contamination that is self-generated within the system.

Developing the contamination profile for a system involves addressing each of these four contamination sources individually. To do so, the designer must consider the amount and type of

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[2] Throughout this document, *contamination* refers to particulate contamination unless otherwise specified.

[3] Note that *contamination* refers to particles expected to be in a system, compared with FOD, which is not expected.

[4] Note that *media* refers to fluids loaded into a system, such as propellant or pressurant, not the filter media.

contaminant that will be encountered during a system's service life, including cleaning, assembly, testing, propellant loading, and flight.

After identifying all contamination contributors and assigning the appropriate cleanliness levels/particle contributions for each, the designer can use load fraction multipliers based on system complexity to obtain total particle counts. These counts can then be converted to the needed holding capacity of the system's filters with an appropriate amount of margin added.

### 8.1.1. Built-In Contamination

It is understood that no matter how well a tank, component, fitting, or tube segment is cleaned, it will always contain some number of particles that will eventually be liberated by fluid once the system enters service. The designer should verify that all cleaning processes align with the flight system operating flowrates and quantities. This built-in contamination is limited by the cleanliness levels typically specified for each component. It is common to specify a cleanliness level with respect to a particular standard (e.g., IEST-STD-1246 level 100 [ref. 5]). A key aspect of specified cleanliness levels is that they are specified as the number of particles per unit of wetted surface area or per unit volume (which is based on area). The built-in contamination for a system is the sum of the contamination for each of its individual parts. Typically, built-in contamination is the largest contributor of particulate in a system.

#### 8.1.1.1. Identify All System Components

The first step in determining the built-in contamination profile of a system is to identify all components capable of contributing contamination, per the following definitions.

- Components: Valves, pumps, lines, tubing, tanks, fittings, and other parts that make up a system. This is the lowest level, where each item has a specified cleanliness requirement.
- Assembly/sub-assembly (interchangeable): A combination of two or more components. This level may or may not have a specified cleanliness requirement.
- System: Made up of components and/or assemblies. This level typically has a specified cleanliness requirement.

This process involves listing all components (and sub-assemblies, if applicable). It is important to note that cleaning and verification can be performed at any of these levels. If an assembly or sub-assembly is specified to be cleaned and verified to a particular level, then that assembly should be assessed as if it were a single component cleaned to that level.

For many systems, however, the filter analysis must be performed before decisions have been made about cleaning at the sub-assembly. Therefore, it is prudent to make the conservative assumption that there will be no cleaning at the sub-assembly level and that all system components will be cleaned individually prior to assembly.

#### 8.1.1.2. Assign Cleanliness Levels to System Components

Once the system components have been identified, cleanliness levels per the relevant specification must be determined and assigned to each component. For components with an unknown cleanliness level, an assumption can be made based on the complexity of the component if sampling is not feasible (e.g., IEST-STD-CC1246 level 50 for a valve or other component; level 25 or 50 for a section of tubing or other piece-part [ref. 5]). It is important to note that all components within a system must be accounted for in this analysis and have a specified cleanliness level to prevent contamination failures.

The cleanliness of internal surfaces is typically determined by flushing a known volume of solvent through the element and counting the number of particles per unit volume in the effluent. Particle counts are most often specified per 100 mL of solvent. This is not to say that 100 mL of throughput will dislodge all particles remaining in the component; otherwise, perfect cleanliness could be achieved by one extra 100-mL flush. Instead, this is based on the observation that the next 100 mL of throughput is expected to dislodge almost as many particles as the previous 100 mL of throughput. As fluid continues to flow through the component, the number of dislodged particles will begin to decrease. As shown in reference 6, the decay in particle generation requires a very large throughput to become significant. It is reasonable to assume for propulsion systems with limited volume throughput (i.e., less than 1000 L) that particle production remains relatively constant as throughput increases. The result of this assumption is that the specified cleanliness level of a particular element can be scaled by the overall volume throughput for that component to determine the total number of particles contributed over the life of the system, as detailed in Section 8.1.6.

#### 8.1.1.3. Constant Particle Decay Approach Limitations

It is noted that the above assumption of constant particle production may break down for recirculating systems (e.g., a refrigerant loop) or for high-throughput flight systems supplied via a ground-based fluid source during vehicle processing (e.g., continuous purge). Given the scarcity of data on the decay in particle production as throughput increases, it is difficult to quantitatively represent this phenomenon in a filter analysis. The solution to date has been to simply ignore the decay rate, a conservative approach. This assumption is reasonable for fluid systems with a smaller total throughput (e.g., in the 10s to 100s of liters and below) [ref. 6]. However, as throughput increases beyond this range, particle shedding begins to fall off appreciably as more of the initially present particulate is flushed away. Sizing a filter for a high throughput system such as a cooling loop or ground-based purge under the “constant particle production” assumption often leads to an unreasonably large capacity requirement. This is an area that warrants further testing. A test campaign in which a variety of fluid system components are cleaned, flushed with a large volume of fluid, and then sampled periodically for particulate would yield valuable data.

### 8.1.2. Contamination Introduced During System Assembly Processes

The second step in the filter analysis is to account for contamination introduced into the system during assembly. This contamination is not considered FOD, as it is an unavoidable byproduct of certain processes. It is expected to be part of the system contamination profile, and must be accounted for in the filter analysis.

Analysis of these processes can be more challenging, as it relies on process control and can be harder to verify without extensive testing. Additionally, the processes are focused on the resulting system-level integrity and reference relevant industry standards. The cleanliness of these processes, however, is not included in standards and is typically left to individual integrators to address. Each vendor is expected to develop assembly processes and document the test verification of the resulting cleanliness impacts per ASTM E1548 contamination control plans [ref. 2].

A number of references identify processes such as welding and the mating of threaded fittings as particle contributors [refs. 6, 8], but due to the variability of these processes, quantifying contamination is left to the individual vendors and system designers.

The primary concern is that the contamination contribution is bound by vendor specification/ documentation for the process. However, particulate generated during some steps can be mitigated with the proper precautions.

- Cleanliness of shield gas (which should be accounted for if not filtered to a sufficient degree) and of weld fixtures may vary from one vendor (and facility) to the next.
- The amount of weld spatter will affect the number particles generated.
- The type of mechanical fitting employed (e.g., AN, MS-Boss, NPT, compression [ref. 9]) and the degree of care during assembly will affect the number of particles generated.
- Lubricants may reduce particles generated by mechanical fittings, but may themselves cause contamination if not carefully selected.
- Cleanliness of the assembly facility.

During the design phase of a system, the integrator and processes are generally unknown and assumptions must be made to perform the filtration assessment. In these situations, it is recommended to count each assembly operation (e.g., weld or mechanical fitting) as a low-level particle contributor. If IEST-STD-CC1246 is the governing cleanliness standard, then welds and fittings can be assumed to contribute at level 25 [ref. 5]. This approach is consistent with the one used in Reference 6, although it should be noted that the reference paper is geared toward smaller, robotic spacecraft. For systems with larger plumbing (i.e., 1 in. OD and larger tubing), there is no substitute for testing at representative conditions. When the testing of these processes is included per ASTM E1548, it is recommended that the results be compared to assessment assumptions to determine impacts [ref. 2].

As shown in the system example in Appendix F, each identified contributor should be added to the list of system components generated per Section 8.1.1. A list of common assembly operations and recommendations for how to account for them is provided below:

- **Welds**
  - Recommendation: Perform site-specific testing to quantify particle contribution.
    - Alternative: Count each weld as a low-level contributor (e.g., Level 25 per IEST-STD-CC1246) [ref. 5].
- **Mechanical Fittings**
  - Recommendation: Perform site-specific testing to quantify particle contribution.
    - Alternative: Count each mechanical fitting as a low-level contributor (e.g., Level 25 per IEST-STD-CC1246) [ref. 5]. Be sure to account for spatter and any unfiltered shield gas used during welding.
- **Cutting (Fit and Trim)**
  - Recommendation: Make every effort to prevent generation of particles during these operations and to prevent particles from falling into sensitive areas; do not otherwise account for cutting operations in the capacity analysis.
  - Recommendation: If cutting and repair operations will be allowed during the assembly process, perform testing to quantify the particulate generated for a typical repair operation.
    - Allow for a set number of such repairs by including the equivalent particle load in the analysis.

- **Environment**
  - Recommendation: Whenever cleaned hardware has been removed from its bag, it should be located in a cleanroom of sufficiently low ISO class, based on system sensitivity.
    - Even in a clean room, unmated tubes/ports/fittings/etc. should be kept bagged, covered, capped, or plugged with clean, non-shedding material until immediately before the open joint will be mated.
    - When these precautions are taken, it is not generally necessary to make additional adjustments to filter capacity due to particle fallout from the assembly environment.
    - The use of fallout witness plates during assembly can still be helpful for confirming that a quantitative adjustment to particle loads is not necessary for a given assembly facility.

In general, contamination introduced during system assembly tends to be a small contributor to the contamination profile. However, due to the number of variables and sole reliance on process control, this is presumed to be a significant contributor to FOD. Note: the use of lubricants to facilitate the assembly of tight-fitting parts can also be a source of contamination.

## 8.1.3. Contamination Loaded into the System with Media

The system boundary should be drawn around flight system/vehicle with clearly defined interfaces. Any fluid loaded into the system must be filtered/controlled to a specified cleanliness level and accounted for in the filtration analysis.

Fluid cleanliness level requirements for a given flight system are usually based on the contaminant sensitivity of its operating components and defined in an ICD. The cleanliness of media loaded into the system should be verified either by sampling or with the use of a “last chance” interface filter installed in the ground support equipment (GSE).

### 8.1.3.1. GSE Considerations

GSE should contain filtration sufficient to meet media cleanliness requirements at the flight hardware interface. In addition to the specific requirements, and due to the critical nature of system components, GSE filtration should follow processes similar to those in design documents for aerospace purposes [refs. 10, 11]. Handling and cleanliness requirements for GSE fluid hardware should ensure cleanliness interface requirements will be met. If design features such as a filter bypass are used, additional features should also be implemented to ensure interface cleanliness requirements are not violated. If components such as flexible lines are used in the system, special attention should be given to ensure cleanliness. Each program should assess the system based on the program’s specific needs and configurations when designing GSE.

Consideration of GSE filter location, capacity, and micron rating is essential to verifying the cleanliness of the flight system’s propellant and pressurant. All GSE filters considered part of a “permanent” facility are typically replaced or cleaned at scheduled intervals, depending on filter holding capacity and system throughput. Note that the filter sizing process described in Section 8.1 can also be used to determine the required holding capacity of GSE filters.

Controls put in place to prevent contamination during the loading process typically include:

- Using clean bags/containers to hold service valve caps, plugs for flex hoses, and quick disconnects when not needed.
- Maintaining cleanliness for tools used to connect or disconnect system components.
- Using clean, lint-free gloves.

Loading environments themselves can inadvertently introduce contamination into the media. These environments can vary in cleanliness and can include ISO-class cleanrooms, gloveboxes, assembly high bays, or the outdoors. The environment will dictate what controls are necessary and feasible. The cleanliness of self-contained atmospheric protective ensemble suits and other personal protective equipment (PPE) must also be considered, since propellant is often loaded by personnel wearing PPE.

The system designer will decide on sampling requirements and whether particulate samples taken at the GSE connection points to the spacecraft are required. In some loading environments, there can be a high potential for sample contamination from external sources. Sample failures can lead to increased cost and schedule delays. Loading systems should be analyzed to identify potential sources of particulate contamination. Controls can then be implemented to reduce sample handling and prevent contamination. If it is determined that propellant/pressurant samples are not required, a "last-chance" GSE filter is typically installed just upstream of the connection point to the flight hardware system. Without sampling, the final GSE filter is used to verify the cleanliness of the loaded fluid. It should be noted that locating the interface filter on the flight system inlet rather than the GSE may limit the ability to pull samples from the loaded system to verify cleanliness without the addition of a test port to serve as a sampling interface.

### 8.1.3.2. Flight System Considerations

All media that pass through the system filter(s) during system assembly[5], testing, check-out and flight contribute to the contamination profile and should be included in the analysis. This includes fluids used for proof and leak checks, purges, and weld shield gas. Once the flight filter(s) are installed, any gas or liquid flowing through them will be considered as media loaded into the system, even if it does not remain onboard during flight. Launch vehicles may be purged for extended periods of time due to unexpected launch delays. The purge gases should be filtered in accordance with the system requirements, and the potential for additional throughput must also be considered.

The specific media to be loaded will typically come with a purity verification from the vendor, usually based on a military specification, such as MIL-PRF-27404 [ref. 12] for monomethylhydrazine. This propellant specification only limits particulate on a mass per volume basis, as shown in Table 8.1-11, not by particle size or counts.

***Table 8.1-1. Chemical and Physical Properties***

| Properties | Limits | Test Paragraph |
|---|---|---|
| Monomethylhydrazine (% by weight) | 98.3 | 4.3.2 |
| Water (% by weight) | 1.5 max | 4.3.2 |
| Non-volatile residue (mg/L) | 10 max | 4.3.3 |
| Particulate (mg/L) | 10 max | 4.3.4 |

Particle distribution requirements for media loaded into a system will typically be established by the system designer after analyzing the system to determine its sensitivity to particulate. While each system's sensitivity will be unique, it has been observed that IEST-STD-CC1246 level 25 is

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[5] There is some overlap with media used during the assembly process, which should be accounted for in either this section or Section 8.1.2, "Contamination Introduced During System Assembly Processes."

commonly used for gases and test fluids, while either level 50 or level 100 is typically used for liquid propellants [ref. 5]. These commonly used particle distribution levels are shown in Table 8.2 and serve only as a guideline.

***Table 8.1-2. Maximum Particle Counts***

| IEST-STD-CC1246E Level (Maximum Particle Count) | | | | |
|---|---|---|---|---|
| **min (µm)** | **max (µm)** | **25** | **50** | **100** |
| 5 | 15 | 19 | 141 | 1519 |
| 15 | 25 | 2 | 17 | 186 |
| 25 | 50 | 1 | 6 | 67 |
| 50 | 100 | 0 | 1 | 9 |
| 100 | 250 | 0 | 0 | 2 |
| 250 | 500 | 0 | 0 | 0 |
| 500 | 750 | 0 | 0 | 0 |
| 750 | 1000 | 0 | 0 | 0 |
| 1000 | 1250 | 0 | 0 | 0 |

It is often necessary for spaceflight fluid systems to include provisions for off-loading of propellants and pressurants. If the off-loading uses the same flow path as the initial loading, care must be taken to prevent the unintentional introduction of particulate into the GSE due to backflow through a filter. A separate interface designed for reverse flow could be used to avoid this potential issue.

Best practices regarding cleanliness of fluids being loaded into spaceflight hardware include:

- Assume the fluid to be loaded contains a large amount of particulate that must be filtered.
- Determine sampling requirements with the understanding that particulate samples are not always an accurate indication of fluid/system cleanliness, due to outside contamination sources.
- Install a point-of-use or last-chance filter just upstream of the service valve or vehicle connection point on the GSE, if possible. It is preferable to have the final filter downstream of as many flex hoses and other flexible elements as possible.
- If possible, filter all loaded fluids to the lowest micron size considered in the filter analysis.

### 8.1.4. Self-Generated Contamination from Within the System

Self-generated contamination, its effects, and mitigations have been documented throughout the history of spaceflight [refs. 13, 14]. It has been shown to be induced chemically and mechanically, individually or in combination, and has been demonstrated to originate from a number of sources. Chemically induced contamination can result from incompatibilities between construction materials and fluids within the system. Mechanically induced contamination can result from degradation in dynamic thermal and mechanical environments, component wear during operation or fluid flow, and intentional component operation products (e.g., pyrovalves).

Each of these sources is unique in the conditions necessary to initiate contaminant generation: time to onset of generation, rate of generation, and characteristics of the contaminant generated.

As a result, the methods required to characterize and predict their impacts on an integrated system are also unique. Ideally, systems would be designed to prevent self-generated contamination, and various documents provide standard approaches for minimizing it. However, due to the complex conditions that lead to self-generated contamination, mitigation designs may also be necessary.

Allowable self-generated contamination should be specified in component and assembly specifications, so that the contribution to the contamination profile can be included in the system filtration analysis. Specifics of the components, materials of construction, operating fluids, operation, and environments must be considered by the system designer. For some components, testing may be required to establish the predicted contaminant level and type of contaminant that will be added into the fluid by the component. The testing should establish the predicted contaminant level and type of contaminant a component will add to the fluid and to determine its wear-in point. The test plan should specify operating conditions and the number of cycles required for wear-in and total service.

#### 8.1.4.1. Component Wear

Components with sliding surfaces, soft seals, and/or moving parts (e.g., valves, regulators, and pumps) can incur wear or damage over time due to friction or galling that creates self-generated contamination. Additively manufactured components and parts using certain processes can create surface roughness that wears over time and generates particulate. Filter components themselves can generate particulate.

In life testing of fluid system components, particulate generation due to component wear is evaluated and quantified. The requirement to perform this evaluation should be included in the Contamination Control Plan. References 13 and 15 provide approaches for performing this evaluation. Vendors often provide particulate generation data for the components they supply. It is the responsibility of the system designer to ensure that component requirements and hardware specifications address the potential for self-generated contamination and that life testing accurately reflects the intended application.

#### 8.1.4.2. Known Products from Component Operation

Some fluid system components are known to generate debris or contamination, as it is inherent to the component operation. These components, such as pyrovalves and burst discs, can include design features that minimize debris and contamination.

Contamination profiles from components that are known to generate debris or contamination should be quantified, and system filtration design should account for their use. Reference 13 provides limited guidance on identifying the contamination profile of these components. Vendors may have in-house processes, which are not publicly documented, to characterize the contamination profile of their components.

Examples of particle counts for pyrovalve actuation and weld repairs are shown in Table 8-3 [ref. 5]. These counts are provided in size ranges consistent with IEST specifications as well as common NASA specifications. The intent is to use the size ranges that match the specifications of other contamination contributors within a given system.

*Table 8.1-3. Particle Counts for Pyrovalve Actuation and Weld Repair*

| Specification allowed particle count per instance | | | | | |
|---|---|---|---|---|---|
| | 5 to 15 μm | 15 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| 3/8" Pyro actuation | 1703 | 429 | 288 | 100 | 34 |
| 3/4" Pyro actuation | 8742 | 1854 | 1068 | 299 | 75 |
| Weld Repair | 600 | 120 | 30 | 8 | 4 |

| Specification allowed particle count per instance | | | | | |
|---|---|---|---|---|---|
| | 5 to 10 μm | 10 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| 3/8" Pyro actuation | 1192 | 941 | 288 | 100 | 34 |
| 3/4" Pyro actuation | 6298 | 4298 | 1068 | 299 | 75 |
| Weld Repair | 450 | 270 | 30 | 8 | 4 |

### 8.1.5. Load Fraction Multipliers

For a simple propulsion system with a single flow path, determination of the total lifetime particulate contribution of a system element is straightforward. Real propulsion systems, however, tend to involve multiple parallel flow paths. The concept of the load fraction (LF) [ref. 6] is a useful tool to account for this.

Consider a system with a single tank feeding two normally closed, pyrotechnically actuated valves (i.e., pyrovalves) in parallel (Figure 8-1). Downstream of the pyrovalves, the plumbing converges and feeds into a single filter. The overall volume throughput of the system is the useable volume of the tank. However, this is not the volume seen by each pyrovalve. On average, each valve experiences half of the total throughput. It can be stated that each valve has a LF of 50%. In this case, two items in parallel with LF=50% are equivalent to the case of a single item with LF=100% (temporarily ignoring the one-time particle contribution due to pyrotechnic actuation for each valve).

Now consider the slightly more complicated case of a single tank feeding two pyrovalves in parallel, which subsequently feed four filters (also in parallel). While the volume throughput for each pyrovalve does not change, the particulate that each sheds is split approximately four ways into the four filters. The overall LF for each pyrovalve is therefore:

LF = [volume fraction through the system element (pyrovalve)] * [volume fraction to each downstream filter]

A reasonable starting assumption may be that each filter experiences an equal share of the propellant, which would put the LF at 50% * 25% = 12.5%. If the filters are expected to experience differing throughputs, as in the case of each filter protecting a single thruster on a spacecraft that uses differential thrusting for control, it becomes necessary to increase the second term in the LF equation. For example, if the GNC concept of operations allows for any one thruster to experience half of the total throughput, the pyrovalve LF would need to be set at 50% * 50% = 25%.

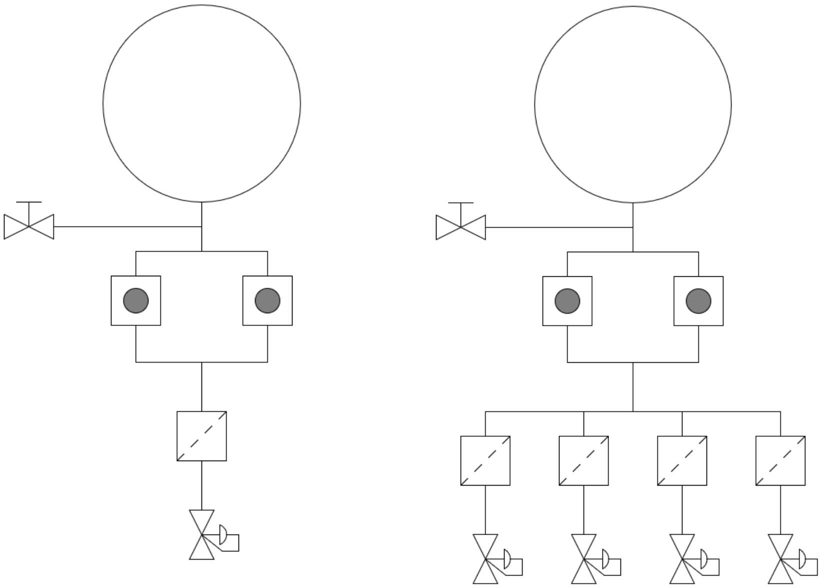

*Figure 8-1. Simple Fluid Systems*
*At left: System containing tank, two pyrovalves, and a filter.*
*At right: Similar system with additional filters in parallel.*

### 8.1.6. Total Particle Counts

Once the load fractions have been determined, the lifetime particulate contributions for each system component can be obtained by scaling the number of allowable particles from each component's cleanliness level by the system's total volume throughput times the LF. This must be done for each particle size range. Repeating this process for each system component and adding up the resulting particle counts yields a conservative bound on the total expected lifetime particle counts due to the system's wetted components identified in Section 8.1.1.

The contamination contributors identified in Sections 8.1.2 and 8.1.4 should be added on a per-instance basis. These contributors can include pyrovalve actuation and weld repair activities, and the multiplying factor is the number of instances for that activity, rather than the LF.

Accounting for the contamination loaded in with the fluid media is dependent on the system requirements typically defined in an ICD. The system designer will establish the cleanliness level of all incoming media as well as the means for verification of the required cleanliness level.

For example, accounting for loaded media contamination may be accomplished by scaling the particle counts of the specified cleanliness level that has been verified via sampling by the total loaded volume. If loaded media sampling is not performed and an appropriately sized GSE interface filter (i.e., one with a micron rating lower than or equal to the smallest particle size considered in the analysis) is used, then the contribution from the loaded media may be ignored in the filtration analysis.

### 8.1.7. Conversion from Particle Counts to Test Dust Mass

The next step in the filter sizing analysis is to convert the total number of particles for each size range, also referred to as bins, to masses of standard test dust. A conservative 2-sigma value of particles per gram of AC Coarse Test Dust (ACCTD) is listed in Table 8.1-4 [ref. 5]. While ACCTD is typically referenced in filter specifications and requirements documents, it is no longer widely available and has been replaced by ISO dust. The assumption is made that ISO dust remains similar to the prior ACCTD for this calculation. Testing to characterize the different available grades of ISO test dust would be valuable. The particle counts shown in Table 8.1-4 include the original size ranges from Reference 6 and the size ranges found in Reference 5. Note that the particle count within a size range is not equal to 1 gram of ACCTD. Instead, 1 gram of ACCTD will have that many particles in each size range shown.

***Table 8.1-4. Particles per Gram of ACCTD***

| Particle count per size range within 1 gram of AC test dust | | | | |
|---|---|---|---|---|
| **5 to 10 μm** | **10 to 25 μm** | **25 to 50 μm** | **50 to 100 μm** | **100 to 200 μm** |
| 28,800,000 | 13,400,000 | 2,940,000 | 530,000 | 76,900 |

| Particle count per size range within 1 gram of AC test dust | | | | |
|---|---|---|---|---|
| **5 to 15 μm** | **15 to 25 μm** | **25 to 50 μm** | **50 to 100 μm** | **100 to 200 μm** |
| 36,400,000 | 5,800,000 | 2,940,000 | 530,000 | 76,900 |

The total particle count within each size range from Section 8.1.6 is divided by the count shown above for the same size range. This will yield the grams of test dust needed to have an equivalent number of particles. The quantity of ACCTD needed to match the size range tends to be larger for lower size ranges. This result is due to a slightly different distribution of particles in ACCTD as compared with distribution assumptions in Reference 5.

### 8.1.8. Filter Dirt Holding Capacity

The final step is to determine the necessary filter dirt holding capacity. This will be based on the test dust mass calculated in Section 8.1.7, but is not simply the sum of masses from each size range. Instead, only the bin that reflects the maximum amount of ACCTD is to be used as the filter design capacity. Note that a typical stacked etched-disk filter traps particles down to half its micron rating, and particles smaller than this can be ignored under most circumstances. Reference 16 discusses situations in which it is prudent to consider particle size ranges slightly below one-half of the filter micron rating. Once the filter holding capacity is identified, the system designer will add an appropriate amount of margin or safety factor. Factors of 2x or 4x are commonly used.

## 8.2 Determine System Filtration Requirements

In this section, the overall contamination profile established in Section 8.1 will determine the most effective system filtration strategy based on what the individual components can tolerate in balance with system design requirements. The goal of system filtration is to protect sensitive components and maintain proper operational behavior. There is no single right answer for the number, type, and placement of filters in a given propulsion system. Trades must be made based on priorities and constraints to optimize the filtration solution. The steps and aspects to consider in determining a filtration solution will remain the same, even though the final design solution may vary for different system applications.

It is important to be aware of how much margin a system filtration design carries and where the margin is being applied. There is no single correct amount of margin. Rather, it depends on program needs and requirements. Since margin can be carried in several ways, it is possible to lose sight of the overall margin for system filtration. This can lead to carrying more margin than intended or needed. In some scenarios, it could also lead to carrying too little margin.

### 8.2.1. Identify Sensitive Components Within the System

Based on the work performed in Section 8.1, the overall system contamination profile has been established. If all system components were insensitive to that size and quantity of contamination, no filter would be required. In most systems, however, components exist that may be detrimentally affected by particulate of a certain size and/or above a certain quantity. Therefore, the next step is to determine what portion of this contamination profile is intolerable to the system or its components and therefore must be filtered. This is done by considering each component within the system to understand what contamination it can and cannot tolerate. Each component may have a different threshold of contamination that can be tolerated. Once established, the best strategy for managing these filtration needs can be weighed at a system level [refs. 13, 17].

Some examples of components that may be sensitive to contamination include most valves, regulators, thrusters, and engines (e.g., turbomachinery and regenerative cooling passages) [ref. 17]. The sensitive features of each component can vary, and each must be assessed individually. Small passages are a common sensitivity because they can become clogged by particulate and/or fiber contaminants. Sealing surfaces are another spot where particulate and/or fiber contaminates can become embedded. If an individual piece or aggregate collection of contaminants is sufficiently large, the sealing ability of the surface may be compromised. Components that have moving elements with tight tolerances and are wetted with propellant may also be susceptible.

Most components will have a critical dimension related to a clearance, orifice size, or similar parameter, such that a particle of that size or larger at that critical location will have a deleterious effect. For the seat-to-seal interface of a valve, the sealing geometry (e.g., seal width and relative flexure) will establish a critical dimension (i.e., particle size that would induce leakage). If multiple smaller particles can induce the same effect, the size of these smaller particles becomes the constraining dimension. For example, an orifice may be blocked by three particles of roughly half the orifice dimension. This leads to a general rule of thumb for using one-half the minimum orifice or clearance in the component as the critical dimension. Further refinement of that geometry may be found in Reference 18. Some degree of margin may be warranted beyond this critical dimension, but the value used becomes part of the mission reliability posture. The resulting value for the critical dimension with margin is then used as the needed filtration rating.

For example, consider an orifice with an internal diameter of 100 μm. The critical dimension is 50 μm, as three football-shaped particles could exactly fit to block that passage. Application of suitable margin may reduce that critical dimension so that 40 μm particles are blocked by the installed filter. Alternatively, a margin factor of 2x would result in a filtration rating need of 25 μm.

The failure modes of components must be evaluated as well. Filtration for components with benign failure modes may be handled differently than those whose failures could have more consequential results. Component protection will be a trade between the number, location, and size of filters in a system. If a particular component is the source of the contamination of most concern (e.g., a pyrovalve), then placement of a filter immediately downstream lessens the impact to the entire system. If there are a few components with higher sensitivity than others, implementing a filter immediately upstream or even as an integral part of the component may be the most efficient approach [ref. 19]. The various strategies for filtration to protect components will be discussed further in Section 8.2.2, considering the system level constraints as well.

### 8.2.2. Determine System Design Constraints

This section identifies some strategies and trades that can be used to optimize the filtration needs of individual system components within the system-level constraints. As previously mentioned, there is no single answer as to the right number, type, and placement of filters for a given propulsion system. For any given system, a range of possible solutions exists.

Filters have mass and volume, and can cause a pressure drop during flow [ref. 17]. The system in which filters are used will place constraints on these parameters. Additionally, there are preferred locations for filters based on contamination generation and contamination sensitivity within the system—that is, downstream of the major contaminant-generating components and upstream of any sensitive components. In the extreme, these constraints may limit the type of filter used or its relative location. While the ideal filter selection and location are based on parameters to maintain a certain level of cleanliness, some systems may be constrained such that a “best possible” solution is used instead.

Allocations of mass and volume are the main parameters that may lead to restrictions or exclusions of the type or location of filter to be implemented. In many heritage liquid propulsion systems, however, filter mass and volume were not significant items of concern. The prudent approach is to determine the appropriate filter and then ascertain if sufficient mass and volume exists within the system at the desired location. Alternate locations should then be explored before reducing the level of cleanliness protection to meet the mass and volume constraints.

Pressure drop allocations are also key in determining the constraint against the ideal filter solution. That is, a total system pressure drop is measured from the source to the final component. Either the system has a maximum pressure drop limit from which the filter gets an allocation, or the system is determined based on a roll-up of assumed pressure drop characteristics. While a clean filter may have a very low pressure drop, the parameter of interest is the maximum allowed pressure drop relating to the particulate quantity that may be trapped. As pressure drop is related to flow rate, the maximum pressure drop is associated with the maximum flow rate. Early in the design process, when the system is little more than a schematic representation, system-level pressure drop is likely the primary design driver. Space Shuttle External Tank Propulsion Data Book [ref. 20] applies some assumptions on calculating pressure drop across screens by utilizing the maximum flow rate. The designer should utilize the same assumptions used to calculate pressure drop across other components when performing system pressure drop calculations. From a filter design standpoint, a lower pressure drop is possible given a larger filter surface area [ref. 17]. The larger area will affect mass and volume and will therefore have practical limitations. Similar to overcoming volume constraints by moving filter location, pressure drop limitations may also be overcome by selecting a different location. For example, moving a single filter on a common leg to two filters on either side of a tee reduces the total pressure drop by ~75% due to the 50% reduction in flow rate through each filter.

Optimization of the filtration approach will depend on program priorities and propulsion system design constraints. Priority can be placed on many different figures of merit, such as minimum part count (e.g., minimum number of unique part numbers or component designs), cost, best schedule/delivery of components, lowest pressure drop, lowest mass, smallest envelope/volume, and fault tolerance. Many of these figures of merit are at odds, such that the optimization of one comes with a penalty to another. Priority may be balanced over several figures of merit, and it is not unusual for these priorities to change between a project's early and later phases. If priorities do change, it is important to seek alternative ways to meet filtration needs rather than reduce filtration requirements.

### 8.2.3. System-Specific Filtration Needs

A variety of unique filtration approaches may be necessary, depending on the fluid commodity being handled and the specific operating parameters (e.g., fluid phase, pressure, flow rate). This section provides examples of unique filtration considerations, but is not intended to be exhaustive.

*Oxidizer Systems*

Oxidizer systems need to be evaluated for ignition hazards [ref. 21]. Since the system contains an oxidizer and the system components (e.g., tanks and lines) are a potential fuel, all that is necessary to create a fire or explosion is an ignition source. The mitigation of ignition hazards in oxidizer systems can result in filtration requirements above and beyond those needed to protect sensitive components.

One potential ignition source is a particle of sufficient mass and kinetic energy to create an ignition upon impact with part of the system. There are several aspects to mitigating this type of ignition hazard in an oxidizer system, such as selecting ignition-resistant materials and sizing the lines and components to reduce flow velocities and the kinetic energy of particulates that are entrained in the flow. In addition to these design considerations, precision cleaning and filtration are used to ensure that the maximum allowable particle size in the system is below the ignition event threshold.

*NTO or MON Systems*

Propulsion systems that use nitrogen tetroxide (NTO) or mixed oxides of nitrogen (MON) must be designed to handle the formation and potential precipitation of iron and aluminum nitrates, which can result from a reaction with iron- and aluminum-containing materials, including stainless steel [refs. 22, 23]. The presence of iron nitrates can also depend on exposure duration, system temperature, flow velocity, moisture content in the propellant, and other factors. This phenomenon has been referred to as *flow decay,* because early experiences often manifested as a reduced flow rate or increased pressure drop. The potential presence of iron nitrates and the factors that can trigger their precipitation must be considered in system filtration choices. If this information is not provided as part of the contamination profile developed in Section 8.1, it should be evaluated as part of the system-level filtration scheme.

*Gas Phase System Filtration*

Filters in pressurant systems can require additional considerations, especially relative to ground handling and ground processing [refs. 6, 13]. Unlike liquid filters, the dynamics of gas flow within a pressurant filter operating in a gravity field alter how particulate is entrained within the filter. The rapid slowing of the gas velocity as it enters the filter case will tend to drop out much of the contaminant it carries. This material can settle in the void space between the filter element and the housing, with little to no particulate reaching the screen. This accounts in part for the generally superior contaminant tolerance of filters in gas use as compared with those in liquid service. In zero-gravity environments, the settling forces are not available. Thus, velocity change causes contaminants to drop out due to gravity; simply rotating the spacecraft during processing can cause contaminant to drop out as well. These effects may drive the need for control of flight hardware handling during ground operations, filtration of test/flight pressurant gas, and prevention of backflow during testing operations. During ground handling and integration processes, special precautions may be needed to avoid orientations in which sensitive components are placed “below” the filters in gas systems or to preclude backflow of gas through the filter. Alternately, the filter can be designed and qualified for structurally being able to handle backflow conditions.

Another unique consideration of gas phase system filtration is the potential attraction of contamination to a static electric buildup on certain materials, such as Teflon parts, in a gas flow environment [ref. 24]. Components that are susceptible to this issue and whose function could be compromised may require additional or different filtration solutions.

### 8.2.4. FOD Screens

In some systems and for some components, there is less of a need to protect against the accumulation of particulate and more of a need to block a few larger particles from harming the component. Consider a system with an upstream filter that feeds into a larger manifold system of lines and components. While standard operational usage provides adequate cleanliness control via the upstream filter, the integration steps in assembling that system, especially repairs to that manifold, may introduce a small quantity of relatively large-size particulate. To protect against that, a FOD screen may be warranted. This application is also sometimes referred to as a *rock catcher.* A FOD screen has no rated dirt-holding capacity, as the expectation is that the value entrapped is small. The FOD screen does have a filtration rating and a pressure drop.

While a filter’s role is to protect against expected contaminants in the system, a FOD screen is intended to protect against unexpected contaminants and debris (i.e., the failure of a component internal to the flow system). Unlike filters, the decision to implement a FOD screen is a subjective assessment based on a risk trade performed as part of a Contamination Control Plan. This trade should determine if a FOD screen is an effective hazard control for unexpected debris, and if so, what size is appropriate. This trade must assess the risk balance between the benefits and drawbacks of implementing a screen in the system, and should consider the performance impacts and hazard likelihood [ref. 25].

Since implementation of a FOD screen can affect system design and operation, a risk trade should be conducted to determine if the likelihood and severity of the hazard outweighs the impacts of the screen. Factors to consider in assessing screen effectiveness include:

a) The failure likelihood of components upstream of the screen or particulate from integration steps.
b) The criticality resulting from the introduction of a contaminant propagating through the system without a screen for protection. If the contaminant size and quantity is benign to system operation, a screen may not be appropriate.
c) The likelihood of system environments causing structural failure of the screen (i.e., the screen could become FOD).
d) The likelihood of particle ignition in a volatile media (i.e., metallic particles in a liquid oxygen system). Implementation of a screen may increase the risk of ignition.

e) How to manage additional leak paths introduced due to the FOD screen system interfaces (e.g., flanges and screen inspection ports).
f) The likelihood of collateral damage due to screen installation/removal and inspection.
g) Any undesirable impacts to stage assembly, processing, or check-out.

FOD screens have no rated dirt holding capacity specified. While area blockage could be calculated, if such blockage were truly possible a more standard filter should be implemented instead to avoid clogging issues and pressure drop increases during flow. Screens typically have a larger micron rating than filters and may be less effective in blocking fibers. Implementation of a FOD screen may have a negative impact on system performance. Therefore, in determining screen size, the designer should consider:

a) The maximum allowable pressure drop across the screen, such that required downstream conditions can still be met. This will drive the selection of screen surface area and filtration level.
b) Operating environments, so the screen can function without degradation.
c) How flow conditions through the screen are altered (e.g., flow profile and thermodynamic conditions), and the prevention of negative performance impacts on downstream system components. Flow conditions across the screen can be estimated analytically, although a flow test is recommended, especially for complex screen geometries [ref. 25]. Testing of filters should be at the component level to test margins, if possible [ref. 26].

Note that the sizing guidelines for filters are applicable to FOD screens and can be used as part of the FOD screen assessment.

## 8.3 Specify Filter Requirements

This section will focus on the unique requirements that should be specified when selecting a filter. For a more complete listing of filter requirements, see Appendix H.

## 8.3.1. Performance Requirements

In general, when writing a requirement for a component, the focus should be on desired performance rather than detailed component design. The following requirements should be considered when specifying filters.

### 8.3.1.1. Filter Rating, Absolute and Nominal

The main filtration requirement is the specified filter rating. The filtration rating of a porous medium is an expression of the particle size that can pass through the medium; it therefore determines the degree of protection a filter provides for downstream components. Particle size is defined as the largest dimension of a solid particulate contaminant and is measured in microns. There are several definitions of filter rating:

- Three atypical ratings:
  - Maximum particle size rating (MPR): All particles with the largest dimension matching or exceeding the micron size are blocked.
  - Glass bead rating (GBR): The size in microns at which all hard, spherical particles matching or exceeding that rating are blocked from passing through the filter.
  - Average/mean filter rating: The size in microns of a filter’s average, or mean, pore diameter.

- Two typical ratings, noting that the definitions vary based on the organization:
  - Absolute filter rating: The micron size corresponding to removal of 100% of all hard, spherical particles (i.e., glass beads) of that size and larger under static blow-down conditions. The absolute rating matches the GBR.
  - Nominal filter rating: Removal of 98%  (other percentages are sometimes used) of all incident particles larger than the stated size, based on a standard contaminant.

The most definitive of the various ratings is the MPR, which controls the maximum (longest) dimension of any particulate contaminant allowed downstream of a filter. The more typical specification, however, is the absolute rating, which refers to the spherical particle size the filter will retain (i.e., no spherical particles of that size or larger will pass through). Because of the spherical particle aspect, the absolute rating controls only the second-largest dimension of contaminant allowed downstream of the filter. The absolute rating may also be referred to as the GBR, as that is a test verification method. Since glass bead tests render the filter unusable, the common test method, especially on flight filters, is a bubble-point test. The bubble-point test consists of wetting the filter with a liquid of known surface tension and then determining the gas pressure required to force a bubble through the wetted pores [ref. 27]. The larger the pore, the lower the pressure at which a bubble or stream of bubbles will form. The correlation of bubble point to equivalent GBR/absolute rating requires knowledge of the filter element configuration and design. Correlation by test is preferred (i.e., both a glass bead and bubble point test on the given filter configuration/design). A similar relationship can be determined to correlate to the MPR for a given filter design. MPR is determined by measuring the largest dimension of particulate passed through during holding capacity tests [ref. 28]. The mapping of bubble point to absolute GBR or from absolute to MPR is specific to the filtration element (design and configuration). These correlations have been established for both twilled double Dutch weave (TDDW) and plain Dutch single weave (PDSW) wire cloth [ref. 14]. The same apparatus providing the bubble point can be also be used to measure the boil point. The boil point can be correlated to the mean filter rating, which is a useful parameter when analyzing the size of particulate in a system that may be caught and thus count against the dirt-holding capacity. Specifying a tolerance range to the filter rating may be preferred [ref. 29]. In this way, the largest particle size that can pass through (thus affecting downstream components) is known, as is the smallest particle size that can affect the dirt-holding capacity.

#### 8.3.1.2. Dirt-Holding Capacity

The performance of a fluid filter will be affected by particulate entrained in the fluid medium. The term *fluid* here refers to a liquid, gas phase, or two-phase medium. Particles smaller than the filtration element pore size will initially pass through, while larger particles will be blocked. As more particles are collected by the filtration element, the pores become completely or partially blocked and the entrapped particulate will provide a finer filtration level than initially provided by the filtration element. If the flow is held at a constant rate, the pressure drop across the filter will rise, while if the inlet pressure to the filter is held constant, the flow rate will decrease.

A filter’s dirt-holding capacity (i.e., holding capacity, dirt capacity) refers to the amount of a standardized contaminant (e.g., ACCTD or the ISO equivalent) that can be put into the filter before the pressure drop vs. flow rate of the appropriate fluid medium through the filter exceeds some maximum allowable value. Note that a filter with a large pore size could have a higher holding capacity value merely because most of the standardized contaminant passes through rather than being collected. Holding capacity and filter rating are interlinked aspects of the filter design. A related term is *filter efficiency*, defined as the ratio of trapped vs. total particles passed through a filter.

The dirt-holding capacity of a filter is affected by the size and number of flow paths as well as configuration or tortuosity. The resulting pressure drop will be affected by contaminant particle size distribution, the nature of the contaminant, the physical characteristics of the fluid medium, and perhaps whether the unit is tested in a gravity field. For example, the gas velocity rapidly slows as it enters the larger cavity of a filtration element. In a gravity field, larger particles may drop out of the gas and collect within the housing but not on the filtration element. As such, the dirt-holding capacity measured on the ground may be higher than if the filter were used in a zero-gravity environment where those settling forces are not present.

#### 8.3.1.3. Flow Rate and Pressure Drop Requirements

As with any component, flow rate and pressure drop requirements are integrally linked. One cannot be specified without the other. Typically, this requirement will specify a maximum pressure drop for a given flow rate condition. (e.g., media, temperature, and flow rate)

Pressure drop requirements for filters are unique relative to other components. In addition to specifying the pressure drop for given media and flow rate, it needs to be specified at the holding capacity (see Section 8.3.1.2) as well as in the “clean” configuration. Perhaps the clean configuration is less obvious, but it is necessary for flight unit acceptance testing.

Filter applications will specify the fluid medium, the range of flow rates of that fluid, and the maximum allowed pressure drop allocation. In a clean filter, the pressure drop is a function of fluid flow rate and a characteristic verified by qualification and acceptance testing. Typically, the maximum flow rate corresponds to the maximum pressure drop. The expected characteristic from the dirt-holding capacity characterization is a curve showing the relationship of standardized contaminant added vs. pressure drop increase for a given flow rate. Typically, the pressure drop remains relatively flat (i.e., unaffected) until a sufficient quantity of particulate is entrapped, at which point a steep rise occurs. For a given application, the dirt-holding capacity can be read off the curve based on the maximum pressure drop allowance. Dirt-holding capacity is established as part of qualification testing and not conducted during acceptance testing, as that would contaminate the filter.

In establishing the curve, the pressure drop will remain keyed to the fluid flow rate and curve resolution will be affected by the contaminant addition rate. Obtaining maximum resolution requires an even, slow, and methodical introduction of the standardized contaminant with a well-controlled fluid flow rate. Sudden contaminant addition may obfuscate the true limit, as will an unsteady flow rate.

The expectation is that maximum flow rates will result in maximum pressure drops, thus establishing the filter’s dirt-holding capacity. Theoretically, the filter configuration could result in more direct impingement and entrapment of particles on the filtration element for flow rates below the maximum. Such an effect would be similar to the potential gravity field effect noted earlier. Care must be taken in establishing the test conditions for the intended application.

If desired, the contaminants in the fluid passed through the filter during the dirt-holding capacity test may be caught and analyzed to determine the MPR.

#### 8.3.1.4. Reverse Flow Requirement and Pressure Drop (if applicable)

Each filter should be assessed to determine if it will be subject to reverse flow. If so, appropriate reverse flow requirements should be implemented.

### 8.3.2. Design Requirements

Typically, a filter is composed of two main parts: a body (or housing) and an element. (Note that some filters have only an element and use an existing structure, such as a component or duct, in place of the filter body.) The body is not unique to filters, and as with other components, it provides the external pressure boundary for the component. The design requirements for pressurized components are adequately addressed in higher-level documents, such as NASA-STD-5019 [ref. 30] and AIAA S-080 [ref. 31], and are not addressed in this document. The filter element, however, is unique to filters (and FOD screens) and will be addressed in more detail.

#### 8.3.2.1. Filter Element

The function of a filter element is to remove harmful particle debris from the fluid line while allowing adequate flow passage, as specified in the filter performance requirements.

#### 8.3.2.2. Element Collapse Pressure Differential

The primary structural design consideration for a filter is the element collapse pressure differential (ECPD). Each filter needs to be assessed to determine the appropriate ECPD requirement based on the specific system conditions in which it will be used. The relevant safety factors for ECPD should be based on structural governing documents such as NASA-STD-5001 [ref. 32]. The application of proof and burst pressure margins are not applicable for the ECPD.

Surge/transient pressures should be taken into account, and special attention should be paid in situations that may include two-phase flow.

If the filter will have reverse flow, a reverse collapse pressure differential should also be specified.

### 8.3.3. Other Design Requirements to Consider

The wetted filter materials should be compatible with the working fluid of the system for a number of reasons, not the least of which is the filter's ability to generate particulate and contamination under the wrong conditions [ref. 33].

One of the guidelines for filter material selection is to use construction materials that are structurally adequate, corrosion- and temperature-resistant, and unlikely to migrate to the system's downstream portions [ref. 18].

#### 8.3.3.1. Sizing for Large Systems

The filter sizing method recommended in this report results in a "holding capacity" requirement for a filter that is specified in terms of mass of a given test dust. For filters with larger filtration ratings (~> 100 micron) test dusts are not readily available.  So an alternate method must be used.

It is not recommended that the Percent Area Coverage (PAC) be used for filter sizing. PAC is intended for use on surfaces such as solar arrays to be able to predict performance degradation.

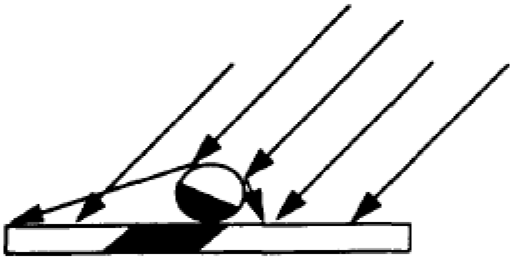

*Figure 8.3.3.1-1: Illustration of PAC [ref. 61].*

Section 3 of Reference 61 provides a more detailed explanation of PAC.

The process recommended for filters with larger filtration ratings is:

- Follow the same process as previously outlined to determine particle counts for each size bin.
- Use the mean particle size of each bin to determine the cross-sectional area, assuming spherical particles. Note: this is conservative, since particles typically are not spherical and have a smaller cross-sectional area.
- Compute the total area to determine blocked area requirement (i.e., equivalent of “dirty” holding capacity in previous discussion).

## 9.0 Contamination Sampling

Several documents indicate procedures for taking particulate samples [refs. 8, 34, 35]. Additional documents provide the procedures for handling and testing those samples for particulate [refs. 36-39]. The procedures listed in Table 9-1 are general and can produce variability in laboratory processes and results.

Based on a wide range of deficiencies uncovered during the study and discussed in other sections, it is important to outline the proper method for taking samples.

### *Table 9-1. Particulate Sampling Procedures*

| | **Liquid Components/Systems Cleanliness Verification** | **Gas Components/Systems Cleanliness Verification** | **Media-Liquid Cleanliness Verification** | **Media-Gas Cleanliness Verification** | **Notes/Rationale** |
|---|---|---|---|---|---|
| **Rinse Sample Process** | Flow should be fully turbulent with a Reynolds number (Re) of ~10,000, or worst-case flight Re, whichever is greater. Whenever possible, components/systems should be configured to allow flow-through rather than a deadheaded configuration. | Flow should have a Re of ~10,000 or worst-case flight Re, whichever is greater.<br>Gravity effects should be taken into account. Flowing in multiple orientations when possible. | Flow should be equivalent to the maximum flow rate used when media is loaded into the vehicle. (May be limited by how the sample is collected.) | Flow should be equivalent to the maximum flow rate used when media is loaded into the vehicle. May be limited by millipore filter delta p. | Based on experience and noted in AIAA 92-3535. |
| **Rinse Sample Volume** | Rinse sample volume should be a MINIMUM of 0.5L/0.1m$^2$ wetted area. | | Sample volume should be a MINIMUM of 0.5L. | | A .5L minimum provides a better representative sample over 0.1L since particles do not leave in a uniform predictable rate. This was recommended in MIL-STD-1774. |
| **Portion of Rinse Sample Volume to be Counted** | Recommend counting particles from 100% of rinse sample.<br>Alternate percentages may be used with approved rationale as to why 100% is not feasible and why the proposed percentage provides a representative sample. | | | | Requiring a 100% sample eliminates taking samples that fail but do not get reported. Also, since the minimum sample is 5x larger than the specified cleanliness volume, the results are effectively an average. This is a logical approach, since cleanliness levels are based on a theoretical distribution. |
| **Number of Samples** | The count resulting from the process and volume addressed above is considered to be one sample, and one passing sample is sufficient. | | | | Multiple samples or a statistical number of samples are not needed for the method recommended herein. |

## 9.1 Chemical Incompatibilities

Although beyond the scope of this assessment, chemical incompatibilities were discussed and are captured in Appendix H.

# 10.0 Findings, Observations, and NESC Recommendations

## 10.1 Findings

The following findings were identified:

**F-1.** The basic parameters that impact the design of a filtration system are:
  a. The largest tolerable particle for each component or assembly within the propulsion or pressurant system.
  b. The maximum pressure drop allocated for the system.
  c. The volume/mass available in the system.
  d. The amount and type of potential contaminant that may be encountered throughout service life.

**F-2.** Historically, filtration system design has not included the contributions of all relevant sources.

**F-3.** A system made up of components cleaned to level 100 may not result in a level 100 clean system, due to the cumulative nature of contamination.

**F-4.** Many filters are inadequately sized for the components and/or systems they are designed to protect.

**F-5.** Qualification and acceptance testing are not always performed for filters used to mitigate hazards in spaceflight programs.

**F-6.** Ground support system filters often receive less testing and analysis than vehicle filters.

**F-7.** Sizing guidelines for filters are applicable to FOD screens and can be used as part of a FOD screen assessment.

**F-8.** A range of acceptable micron ratings in the filter design specification (i.e., maximum and minimum micron ratings) ensures proper margins.

**F-9.** This filtration sizing process, its identified gaps, and its challenges may be applicable to a range of systems beyond propulsion.

**F-10.** Understanding filter flow and differential pressure test data as a function of contamination loading are keys to determining system performance margins.

**F-11.** Contaminant Control Plan guidance has historically included requirements to determine the contamination generation profile of components when purchased. However, recent guidance has omitted this direction.

**F-12.** There is no evidence that the IEST-STD-CC1246E requirement for 95% confidence limits on contamination samples to verify cleanliness level has ever been implemented.

## 10.2 Observations

The following observations were identified:

**O-1.** Design of adequate system filtration assumes ground support systems and servicing media meet their contamination requirements.

**O-2.** Industry processes and methods for determining cleanliness vary widely.

**O-3.** The methods for gathering cleanliness verification samples and counting the particles vary across industry and are typically vendor-proprietary.

**O-4.** The lack of consistency in counting contamination particles results in different filtration system requirements.

**O-5.** Cleaning at both lower and higher assembly levels will reduce the needed system filtration holding capacity.

**O-6.** Particulates can settle in low flow velocity or stagnation regions in a 1-g environment and then move through the system in low or negative-g environments.

**O-7.** A FOD screen is intended to protect against unexpected contaminants and debris, and the decision to implement a FOD screen is based on subjective judgment.

**O-8.** There is a lack of test data on component contamination generation.

**O-9.** Filter micron rating is based on model correlations rather than direct measurements.

**O-10.** The particle size distribution test dust is used because it is readily available.

**O-11.** The particle size distribution of test dust as measured by JPL is similar to the distribution in IEST-CC1246 cleanliness levels.

## 10.3 NESC Recommendations

The following NESC recommendations were identified and are directed toward the NASA OCE, unless otherwise identified:

**R-1.** Requirements documents for fluid systems should include predicted contamination generation and sensitivity characteristics. ***(F-1)***

**R-2.** Filter specifications should include flow and pressure differential requirements for a clean filter and a filter at the specified holding capacity (directed to OCE and flight programs). ***(O-7)***

**R-3.** System cleanliness should be an assessment of the entire system, including internal and external contributors, ground support systems, and media cleanliness levels (directed to OCE and flight programs). ***(F-2)***

**R-4.** A system's filtration requirements should be based on the contaminant sensitivity of its operating components. ***(F-4)***

**R-5.** All filter performance should be verified through qualification and acceptance testing (directed to OCE and flight programs). ***(F-5)***

**R-6.** Ground support system filters should receive the same testing and analysis as vehicle filters (directed to OCE and ground support programs). ***(F-6)***

**R-7.** The effects of acceleration on the settling/unsettling and filtering of particulates in the system should be considered during the design of filtration systems (directed to OCE and flight programs). ***(O-6)***

**R-8.** Updated contamination profiles and ISO test dust standards should be developed and correlated to test data. ***(O-11, O-12)***

**R-9.** The processes and guidelines developed in this effort should be assessed for applicability to spacecraft closed-loop and air revitalization systems (directed to OCE and flight programs). ***(F-9)***

**R-10.** Size, quantity, and type of particulate matter generated by a component under life cycle operating conditions and as a result of post-fluid exposure should be recorded as part of verification activities (directed to OCE and flight programs). ***(F-5, O-8)***

**R-11.** Implement the contamination sampling process outlined in Table 9-1 of this report in lieu of the IEST-STD-CC1246E requirement for 95% confidence limits. ***(F-12)***

# 11.0 Alternative Viewpoint(s)

No alternative viewpoints were identified during the course of this assessment.

# 12.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

# 13.0 Lessons Learned

No lessons learned were identified during the course of this assessment.

# 14.0 Recommendations for NASA Standards and Specifications

No recommendations for NASA standards and specifications were identified as a result of this assessment.

# 15.0 Definition of Terms

| | |
|---|---|
| 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. |
| Observation | A noteworthy fact, issue, and/or risk, which may not be 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 provided. |
| 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. |

## 16.0 Acronyms and Nomenclature

|  |  |
|---|---|
| ACCTD | AC Coarse Test Dust |
| AIAA | American Institute of Aeronautics and Astronautics |
| ASTM | American Society for Testing and Materials |
| ATP | acceptance test program |
| ECSS | European Cooperation for Space Standardization |
| ECPD | Element Collapse Pressure Differential |
| FOD | Foreign Object Debris |
| g | Gravity |
| GBR | Glass Bead Rating |
| GC-MS | Gas Chromatography–Mass Spectrometry |
| $GO_2$ | Gaseous Oxygen |
| GSE | Ground Support Equipment |
| ICD | Interface Control Document |
| ICP-MS | Inductively Coupled Plasma Mass Spectrometry |
| IEST | Institute of Environmental Sciences and Technology |
| ISO | International Organization for Standardization |
| JPL | Jet Propulsion Laboratory |
| L | liter |
| LC-MS | Liquid Chromatography–Mass Spectrometry |
| LF | Load Fraction |
| $LO_2$ | Liquid Oxygen |
| micron | $10^{-6}$ meters |
| mg | Milligram |
| mL | Milliliter |
| MON | Mixed Oxides of Nitrogen |
| MPR | Maximum Particle Size Rating |
| NESC | NASA Engineering and Safety Center |
| NTO | Nitrogen Tetroxide |
| NVR | Non-Volatile Residue |
| OCE | Office of the Chief Engineer |
| PAC | Percent Area Coverage |
| PDSW | Plain Dutch Single Weave |

| | |
|---|---|
| PPE | Personal Protective Equipment |
| PRACA | Problem Reporting Analysis and Corrective Action |
| TDDW | Twilled Double Dutch Weave |
| Ti | Titanium |

# 17.0 References

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2. Standard Practice for Preparation of Aerospace Contamination Control Plans, ASTM E1548-09, ASTM International, West Conshohocken, PA, September 1, 2017.
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## Appendices

A. Literature Reviewed
B. Filtration and Contamination Terminology
C. Vendor Survey Results
D. Lessons Learned
E. System Filtration Design Process
F. Step-by-Step Filtration System Design Process
G. Example System
H. Chemical Incompatibilities
I. Filter Requirements

# Appendix A. Literature Reviewed

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| NAS 9-11264 | Shuttle Filter Study Vol 1, Characterization and optimization of filter devices | Considered the "go-to" for designing filters | | | "Characterization and optimization of filter devices, Shuttle Filter Study Volume 1," NAS 9-11264, Wintec Division, Brunswick Corporation, Los Angeles, California, June 1974. |
| NAS 9-11264 | Shuttle Filter Study Vol 2, Contaminant Generation and Sensitivity | Considered the "go-to" for designing filters | | | "Contaminant Generation and Sensitivity, Shuttle Filter Study Volume 2," NAS 9-11264, Wintec Division, Brunswick Corporation, Los Angeles, California, June 1974. |
| NAS 9-11264 | Shuttle Filter Study Vol 3, Appendix | Considered the "go-to" for designing filters | | | "Appendix, Shuttle Filter Study Volume 3," NAS 9-11264, Wintec Division, Brunswick Corporation, Los Angeles, California, June 1974. |
| NASA SP-8123 | Design Criteria: Liquid Rocket Lines, Bellows, Flexible Hoses, and Filters | This covers several components (including filters) but has good insight into overall system filtration. | | Specifies the four ways contamination enters a system | Daniels, C. M.: "Design Criteria: Liquid Rocket Lines, Bellows, Flexible Hoses, and Filters," NASA SP-8123, NASA Lewis Research Center, Cleveland, Ohio, June 1977. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| MIL-STD-1246A | Product Cleanliness Levels and Contamination Control Program | Original specification for cleanliness levels. Most current specs are based on this document | | Indicates particle distribution is based on "naturally occurring particulate contamination," which is likely not relevant to flowing prop systems. | "Product Cleanliness Levels and Contamination Control Program," MIL-STD-1246A, Department of Defense, Washington, D.C., 19 December 1962. |
| MIL-STD-1246B | Product Cleanliness Levels and Contamination Control Program | Rev B | | | "Product Cleanliness Levels and Contamination Control Program," MIL-STD-1246B, Department of Defense, Washington, D.C., 18 August 1967. |
| MIL-STD-1246C | Product Cleanliness Levels and Contamination Control Program | Rev C | | | "Product Cleanliness Levels and Contamination Control Program," MIL-STD-1246C, Department of Defense, Washington, D.C., 11 April 1994. |
| IEST-STD-1246D | Product Cleanliness Levels and Contamination Control Program | This is a continuation of the MIL-STD-1246 | Provides a good historical background for MIL-STD-1246; supports its lack of applicability to internal prop system cleanliness. | | "Product Cleanliness Levels and Contamination Control Program," IEST-STD-1246D, Institute of Environmental Sciences and Technology, Arlington Heights, IL, December 2002. |
| IEST-STD-1246E | Product Cleanliness Levels and Contamination Control Program | Rev E | | | "Product Cleanliness Levels - Applications, Requirements, and Determination," IEST-STD-1246E, Institute of Environmental Sciences and Technology, Arlington Heights, IL, February 2013. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| AIAA 90-1941 | Propulsion System Filter Sizing Considerations for the Galileo Spacecraft | First documented process for end-to-end contamination prediction and filter sizing/testing | | First data predicting contamination generation decay rates | Jan, D. ; Guernsey, C. ; Callas, J.: "Propulsion System Filter Sizing Considerations for the Galileo Spacecraft," AIAA 90-1941, Jet Propulsion Laboratory, Pasadena, Calif., July 1990. |
| AIAA 92-3535 | A Procedure for Sizing Propulsion System Filter Capacity | Similar to AIAA 90-1941 | | Similar to AIAA 90-1941 | Jan, D. ; Guernsey, C. ; Callas, J.: "A Procedure for Sizing Propulsion System Filter Capacity," AIAA 92-3535, Jet Propulsion Laboratory, Pasadena, Calif., July 1992. |
| JPL 353APS-91-072 | JPL Section 353 Filter Capacity Design Criteria | Internal JPL documents that formed documented their filter sizing process. | AIAA filter sizing papers are based on this JPL process. | First data predicting contamination generation decay rates | Jan, D. ; Davies, M.: "JPL Section 353 Filter Capacity Design Criteria," JPL353APS-91-072, Jet Propulsion Laboratory, Pasadena, Calif., March 1991. |
| JPL 353FSA-91-022 | JPL Section 353 Filter Capacity Design Criteria. Addendum | Internal JPL document that updates their filter sizing process to include tolerances for the specified filter rating. | | Recognizes that specifying the maximum absolute micron rating of the filter is not sufficient. | Jan, D.: "JPL Section 353 Filter Capacity Design Criteria. Addendum," JPL 353FSA-91-022, Jet Propulsion Laboratory, Pasadena, Calif., October 1991. |
| JPL Spec FS504574C | Detail Specification for General Cleaning Requirements for S/C Propulsion Systems and Support Equipment | Internal JPL document that details the precision cleaning process. | | Includes specification for "Class D" cleanliness levels used in JPL 353APS-91-072 | Cannova, R. D.: "Detail Specification for General Cleaning Requirements for S/C Propulsion Systems and Support Equipment," JPL SPEC FS504574C, Jet Propulsion Laboratory, Pasadena, Calif., May 1974. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| ER33-15-003 | Use of Filters and Screens for System Contamination Hazard Controls | ER33 recommended filter sizing process (that follows JPL method) | | This includes a definition for FOD screens that are separate from filters. | Ward, W. K.: "Use of Filters and Screens for System Contamination Hazard Controls," ER33-15-003, Marshall Space Flight Center, Huntsville, AL, July 2015. |
| SE-F-0044A | Specification for Wire Cloth Type Filters | Specifies general requirements for designing wire cloth filters | | Material Compatibility, Number of Qual Units 3, Packaging, Labeling, Bubble Point per ARP 901, Cleanliness per ARP 599A, Drying, Contaminant Tolerance and Maximum Particle Size. Contamination loading and collapse test, lot acceptance testing of a unit to qual requirements, weld requirements, wire cloth repair requirements, cleaning and passivation after welding | "Specification for Wire Cloth Type Filters," SE-F-0044A, Johnson Space Center, Houston, Texas, July 1982. |
| SE-F-0044B | Specification for Wire Cloth Type Filters | Rev B | | | "Specification for Wire Cloth Type Filters," SE-F-0044B, Johnson Space Center, Houston, Texas, May 1987. |
| Filters 5-88 SE-S-0073 and SE-F-004 | | | | | |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| ISO 15859 Fluid Sampling and Test | Revision of ISO15859 Aerospace Fluid Standards | May be stale (2004? vintage), but looks at shifting NASA standards into ISO versions. | Work performed by Ben Greene and Mark McClure, WSTF. Has maps to 13 fluids and outlines comparison efforts to NASA, SSP, ASTM, etc. | May be more work that was performed by WSTF? Looks at not just fluid spec, but also some references to systems cleanliness. | Greene, B.; McClure, M.: "Revision of ISO15859 Aerospace Fluid Standards," ISO 15859, NASA Johnson Space Center, White Sands Test Facility. |
| Open Issues with Filter Dirt Capacity Analysis | | PowerPoint that discusses analytical disparity between system cleanliness and dirt capacity | | | Mueller, M. J.: "Open Issues with Filter Dirt Capacity Analysis," Vehicle Performance Division, The Aerospace Corporation, February 2021. |
| SSP-30573 | Space Station Fluid Procurement and Use Spec for ISS | Detailed information on procurement quality and cleanliness requirements, system cleaning procedures, filtering levels, testing approaches and hardware, and verification (esp. ref sect. 4.1.1). | One of the better (best) efforts defining the systems expectations for complicated and complex system build by numerous providers. Very clear on expectations. | Gold standard of standards on defining expectations for development and operations of a fluid system related to cleanliness and verification. | Yuen, C.H.: "Space Station Fluid Procurement and Use Control Specification for ISS," SSP-30573, NASA Johnson Space Center, Houston, Texas, May 2016. |
| SSP57000 | Pressurized Payloads IRD for ISS, Rev E | Details all the interface requirements for subject payloads to be installed in the ISS. | Excellent reference on implementation of requirements, including verification. See 4.3.11.2/3. | Focus on full systems aspect during verification, system shall be tested to show that contamination was not introduced during manufacturing, assembly and integration. | Geiger, W. C: "Pressurized Payloads Interface Requirements Document," SSP57000, NASA Johnson Space Center, Houston, Texas, November 2000. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| 80900200103 | Space Shuttle External Tank Propulsion Data Book | Specifications and operating requirements for the Super Lightweight External Tank (SLWT) propulsion system. | Section 4.3, Propellant Screens | Provides relevant analysis for verification. Split into loading operations, powered flight operations, and propulsion hardware (most relevant) | LaLanne, R.: "Space Shuttle External Tank Propulsion Data Book," 80900200103, Propulsion Analysis Group, Lockheed Martin, January 2005. |
| 55583 - | Controlling Cleanliness in the Saturn V First Stage. 1968 | Gives good overview of the motivation behind contamination control and the measures put in place to control ground-contamination on Saturn 5 | Gives overview of high-level approach and organizes process and environmental requirements. | Environmental requirements, cleaning and testing media requirements, final cleanliness requirements | Colson, S.; Hartman, J.: "Controlling Cleanliness in the Saturn V First Stage," 55583-, The Boeing Company, New Orleans, Louisiana, March 1968. |
| AAS 13-457 | Lessons Learned from the Development of the MSL Descent Stage Propulsion System | Overview of lessons learns in development of MSL descent stage propulsion system, including surprises and anomalies | | Descent RCS thruster valve met the spec, but material conditions caused failure | Guernsey, C. S.; Weiss, J. M.: "Lessons Learned from the Development of the MSL Descent Stage Propulsion System," AAS 13-457, Jet Propulsion Laboratory, Pasadena, California, 2013. |
| AIAA 2000-3633 | Contamination Control Engineering for Aerospace Fluid Power/Propulsion Applications -- Concept To Flight | Examines contamination risks in propulsion systems and considerations required for very clean hardware | Preflight cleanliness requirements and procedures | | Bauer, J. W.: " Contamination Control Engineering for Aerospace Fluid Power/Propulsion Applications -- Concept To Flight," AIAA 2000-3633, Space Products Division, Moog Inc., East Aurora, New York, July 2000. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| AIAA 2001-3630 | Propulsion Lessons Learned from the Loss of Mars Observer | Overview of likely causes for signal loss from Mars Observer, attributed to incompatible braze material in pressure regulator flow restriction orifice | | Over-reliance on heritage designs is common between failure modes | Guernsey, C. S.: "Propulsion Lessons Learned from the Loss," AIAA 2001-3630, Jet Propulsion Laboratory, Pasadena, California, July 2001. |
| ASTM E 2016-11 | Standard Specification for Industrial Woven Wire Cloth | Establishes tolerances, requirements, and woven specifications of woven wire cloth filters | | Correlations and specifications for woven wire cloth filters | "Standard Specification for Industrial Woven Wire Cloth," ASTM E 2016-11, ASTM International, West Conshohocken, PA, April 2008. |
| ASTM E128 | Standard Test Method for Maximum Pore Diameter and Permeability of Rigid Porous Filters for Laboratory Use | Details test method for determining maximum pore diameter and permeability of rigid porous filters. | | Equation derived for pore diameter | "Standard Test Method for Maximum Pore Diameter and Permeability of Rigid Porous Filters for Laboratory Use," ASTM E128, ASTM International, West Conshohocken, PA, 2011. |
| ASTM E1548 | Standard Practice for Preparation of Aerospace Contamination Control Plans | Overview of cleanliness requirements and operational efforts for meeting requirements. | Details administrative processes for contamination control | | "Standard Practice for Preparation of Aerospace Contamination Control Plans," ASTM E1548, ASTM International, West Conshohocken, PA, April 2009. |
| ASTM E1548-09 | Standard Practice for Preparation of Aerospace Contamination Control Plans | Overview of cleanliness requirements and operational efforts for meeting them. | | Details administrative processes for contamination control | "Standard Practice for Preparation of Aerospace Contamination Control Plans," ASTM E1548, ASTM International, West Conshohocken, PA, April 2017. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| ASTM F302 | Standard Practice for Field Sampling of Aerospace Fluids in Containers | Overview of procedure for taking representative fluid sample from a hermetically sealed container for analysis. | Uses Practice F311, Test Method D4898, and Test Method F314 | | "Standard Practice for Field Sampling of Aerospace Fluids in Containers," ASTM F302, ASTM International, West Conshohocken, PA, April 2015. |
| ASTM F303 | Standard Practices for Sampling for Particles in Aerospace Fluids and Components | Overview of three sampling procedures for determining particle cleanliness of liquid and liquid samples. | Defines:<br>1) Static fluid sampling<br>2) Flowing fluid sampling (says min flow rate is 500 mL/min)<br>3) Rinse fluid sampling | Recommends 100% sample collection since particles do not leave component at a uniform predictable rate. | "Standard Practices for Sampling for Particles in Aerospace Fluids and Components," ASTM F303, ASTM International, West Conshohocken, PA, April 2016. |
| ASTM F311 | Standard Practice for Processing Aerospace Liquid Samples for Particulate Contamination Analysis Using Membrane Filters | Details procedure for using membrane filters to prepare samples for liquid particulate contamination analysis | Analyzed with ASTM F312 | Particle size: 2-1000 micron | "Standard Practice for Processing Aerospace Liquid Samples for Particulate Contamination Analysis Using Membrane Filters," ASTM F311, ASTM International, West Conshohocken, PA April 2013. |
| ASTM F312 | Standard Test Methods for Microscopical Sizing and Counting Particles from Aerospace Fluids on Membrane Filters | Details method for sizing and counting particles sampled with a membrane filter | Two sizing methods: 1) projected area, 2) longest dimension | | "Standard Test Methods for Microscopical Sizing and Counting Particles from Aerospace Fluids on Membrane Filters," ASTM F312, ASTM International, West Conshohocken, PA, 2016. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| ASTM F316 | Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test | Method for determining pore size properties of membrane filters:<br>1) maximum limiting pore diameter,<br>2) relative abundance of specified pore size. | Applicable for .1 to 15 micron | | "Standard Test Methods for Pore Size Characteristics of Membrane Filters by Bubble Point and Mean Flow Pore Test," ASTM F316, ASTM International, West Conshohocken, PA, 2003. |
| ASTM F327 | Standard Practice for Sampling Gas Blow Down Systems and Components for Particulate Contamination by Automatic Particle Monitor Method | | | | "Standard Practice for Sampling Gas Blow Down Systems and Components for Particulate Contamination by Automatic Particle Monitor Method," ASTM F327, ASTM International, West Conshohocken, PA, 2016. |
| ASTM G93-03 | Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments | Details administrative control and process selection considerations for cleaning items in oxygen-enriched environments. | Details levels of cleanliness used for various applications and verification methods. | | "Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments," ASTM G93-03, ASTM International, West Conshohocken, PA, April 2016. |
| CxP 70145 | Constellation Program Contamination Control Requirements | Establishes common, minimum requirements and controls necessary for contamination control of ground systems and flight hardware. | Information on cleanliness levels and test/verification methods but no mention of filters | | "Constellation Program Contamination Control Requirements," CxP P 70145, NASA, 2007. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| Impact of ISO Changes | Impact of Changes to ISO Standards on Contamination Control Programs | Overview of ISO change from AC Fine Test Dust and impact on particle counter calibrations and filter testing. | Relevant to systems/filters not using ACFTD for verification/test. |  | Bensch, L.: "Impact of Changes to ISO Standards on Contamination Control Programs," Impact of ISO Changes, Pall Corporation. |
| ISO 12103-1 | Road Vehicles — Test Dust for Filter Evaluation | Specifies four grades of test dust made from desert sand. Dusts are used to determine performance of motor vehicle filtration systems. | Not appropriate for particle counter calibration |  | "Road Vehicles — Test Dust for Filter Evaluation," ISO 12103-1, International Organization for Standardization, 1997. |
| ISO 14624-5 | Space systems — Safety and Compatibility of Materials | Specifies test equipment and techniques used to identify interactions resulting from exposure of a material to an aerospace fluid (specifically propellants) | Doesn't account for degradation as a function of time and not suitable for long term exposure (>12 months) | Doesn't cover filters | "Space systems — Safety and compatibility of materials," ISO 14624-5, International Organization for Standardization, 2006. |
| ISO 5011 | Inlet Air Cleaning Equipment for Internal Combustion Engines and Compressors — Performance Testing | Specifies test procedures for direct performance comparison of air cleaners used in internal combustion engines and compressors. | Performance characteristics of interest: 1) air flow restriction, 2) dust collection efficiency, 3) dust capacity,<br>4) oil carry-over | Automotive and industrial applications | "Inlet Air Cleaning Equipment for Internal Combustion Engines and Compressors — Performance Testing," ISO 5011, International Organization for Standardization, 2014. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| ISO DIS 2942 | Hydraulic fluid power — Filter elements — verification of fabrication integrity and determination of first bubble point | Specifies bubble point test method for filter elements used in hydraulic fluid power systems. | Uses are verification of filter element and to permit the localization of the largest pore of the filter element. |  | "Hydraulic Fluid Power — Filter Elements — Verification of fabrication integrity and determination of the first bubble point," ISO DIS 2942, International Organization for Standardization, 2018. |
| JSC-18958 | Shuttle Prop OMS/RCS filters | Describes mechanisms of particulate contamination and the types of filters present in OMS/RCS to prevent impacts on system performance. | Only the filter section | Gives structured overview of filter and contaminant related failure experience from AJRD during Apollo (1.1.3.6) | "Shuttle Prop OMS/RCS filters," JSC 18958, Johnson Space Center, Houston, Texas, December 2000. |
| JWS-023-04MP | TVC Fuel Filter Inspection | Documents procedure and results from sectioning a fuel filter to inspect for contamination, corrosion, or degradation. | Used "fleet leader" fuel filter with 8 flights. | Contamination from Krytox fluorinated grease, no corrosion or degradation of welds. | "TVC Fuel Filter Inspection," JWS 023 04MP, United Space Alliance, December 2004. |
| KSC-C-123H | Surface Cleanliness of Fluid Systems, Specification for | Specifies surface cleanliness levels, test methods, cleaning/packaging requirements, and protection/inspection procedures for determining surface cleanliness. | Specifies requirements for various cleanliness levels |  | "Surface Cleanliness of Fluid Systems, Specification for," KSC-C-123H, NASA Kennedy Space Center, 2000. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| MA0110-301 | Product Cleanliness Spec | Defines standard levels of surface cleanliness requirements and verification. | | | "Product Cleanliness Specification," MA0110-301, The Boeing Company, 2004. |
| MA0110-311 | Contamination Control During Manufacture and Checkout of the Orbiter Vehicle | Establishes minimum contamination control requirements during manufacturing, test, and checkout of the Orbiter vehicle. | Doesn’t provide much justification for fluid system requirements. | | "Contamination Control During Manufacture and Checkout of the Orbiter Vehicle," MA0110 311, The Boeing Company, 1989. |
| MA0610-017 | Precision Cleaning Methods and Cleanliness Requirements for Parts and Assemblies of Apollo CSM Fluid Systems | Establishes minimum precision cleaning requirements for parts and assemblies of Apollo CSM pressurizing and fluid systems. | Defines cleanliness levels and the materials/process required to reach each level for the Apollo CSM | Does not apply to storable propellant decontamination. | " Precision Cleaning Methods and Cleanliness Requirements for Parts and Assemblies of Apollo CSM Fluid Systems," MA0610 017, Space Division, North American Rockwell Corporation, 1971. |
| ME286-0056 (He Filter) | Filter, Helium | | | | "Filter, Helium Specification Control Drawing," ME286-0056, Space Division, Rockwell International, Downey, California, May 1980. |
| MIL-F-8815 | Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 Micron Absolute and 5 Micron Absolute | Establishes specifications for hydraulic line filter assemblies and elements that retain particles larger than 15 microns and 5 microns. | Paragraph 4.7.2.4.2 details test method for filter element efficiency. | | "Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 Micron Absolute and 5 Micron Absolute - General Specification for," MIL-F-8815D, U.S. Department of Defense, September 1976. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| MIL-PRF-27401g | Performance Specification Propellant Pressurizing Agent, Nitrogen | Specifies requirements for gaseous and liquid nitrogen of varying grades a, b, c | | Filter requirements discussed in 4.3. Particulate content verification method discussed in 4.4.3. | "Performance Specification Propellant Pressurizing Agent, Nitrogen," MIL-PRF-27401F, U.S. Department of Defense, January 2008. |
| MIL-STD-1774 | Process for Cleaning Hydrazine Systems and Components | Establishes cleaning level requirements and instructions for cleaning hydrazine storage and flight systems | Standard was canceled. | | "Process for Cleaning Hydrazine Systems and Components," MIL-STD-1774, U.S. Department of Defense, April 1982. |
| MIL-STD-1774_Cancellation | Cancellation notice for MIL-STD-1774 | Official cancellation notice | Provides no background or reasoning for cancellation. | Canceled without replacement. | "MIL-STD-1774 Notice of Cancellation," MIL-STD-1774-Cancellation, U.S. Department of Defense, December 1995. |
| MQ29434_Pleated Filter Analysis | Analysis of Pleated Air Filters Using Computational Fluid Dynamics | Examines effect of pleat geometry(shape, height, spacing), approaching air velocity, and filter configuration on the flow pattern and pressure drop across pleated filters. | | Obtained generalized correlation for the design of triangularly pleated air filters. | Tsang, C. M.: "Analysis of Pleated Air Filters Using Computational Fluid Dynamics," Graduate Department of Mechanical and Industrial Engineering, University of Toronto, 1997. |
| MSFC-PROC-404 | Procedure Gases, Drying and Preservation Cleanliness Level and Inspection Methods | Establishes cleanliness and testing requirements for gasses used in cleaning, testing, drying, etc. | Specifies cleanliness requirements at gas utilization points. | Section 6.1.1.1 particulate matter limits | Nerren, B. H.: "Procedure Gases, Drying and Preservation Cleanliness Level and Inspection Methods," MSFC-PROC-404, NASA Marshall Space Flight Center, Huntsville, Alabama, 1988. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| MSFC-SPEC-164B | Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems, Specification for | Establishes surface cleanliness requirements of components and associated ground support equipment. | Minimum cleanliness levels in paragraph 3.2 and Table 2. | | Griffin, D. E.: "Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems, Specification for," MSFC-SPEC-164B, Marshall Space Flight Center, Huntsville, Alabama, 1994. |
| MSFC-SPEC-164D | Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems, Specification for | Establishes surface cleanliness requirements for oxygen, fuel, and pneumatic components used in space vehicle fluid systems and associated ground support equipment. | Focuses more on oxygen, fuel, and pneumatic systems than Rev b | | "Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems, Specification for," MSFC-SPEC-164D, Marshall Space Flight Center, Huntsville, Alabama, 2014. |
| MSFC-STD-246D | Standard Design and Operational Criteria for Controlled Environmental Areas | MSFC standard for contamination control of environmental controlled areas, cleanrooms, flow benches, and unidirectional clean air devices. | | Specifies minimum environmental control operating standards for rooms and hardware | " Standard Design and Operational Criteria for Controlled Environmental Areas," MSFC-STD-246D, Marshall Space Flight Center, Huntsville, Alabama, 2011. |
| N88-25397 | Space Station Particulate Contamination Environment | Covers adherence and subsequent release of pre-launch particulate contamination during space flight. | Details pre-launch contamination sources and mechanisms of release into system. | | Miller, E. R.; Clifton, K. S.: " Space Station Particulate Contamination Environment," N88-25397, Space Science Laboratory, Marshall Space Flight Center, Huntsville, Alabama. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| NAS412 | Foreign Object Damage/Foreign Object Debris Prevention | | | | "Foreign Object Damage/Foreign Object Debris Prevention," NAS412, Aerospace Industries Association, 2013. |
| NASA CR 4740 | Contamination Control Engineering Design Guidelines for the Aerospace Community | | | | Tribble, A. C.: "Contamination Control Engineering Design Guidelines for the Aerospace Community," NASA CR 4740, Rockwell International Corporation, Downey, CA, May 1996. |
| NASA LLKN 1334 | Cleanliness of Diaphragm Propellant Tanks, NASA - Lessons Learned Knowledge Network | | | | Guernsey, C. S.: "Cleanliness of Diaphragm Propellant Tanks, NASA - Lessons Learned Knowledge Network," NASA LLKN 1334, Jet Propulsion Laboratory, Pasadena, CA, 2003. |
| NASA SP-8097 | Liquid Rocket Valve Assemblies | | | | "Liquid Rocket Valve Assemblies," NASA SP_8097, November 1973. |
| NASA SP-5076 | Contamination Control Handbook | | Doesn't mention internal cleanliness for prop systems. | | "Contamination Control Handbook," NASA SP-5076, Sandia Laboratories/ Marshall Space Flight Center, 1969. |
| NASA SP-8080 | Liquid Rocket Pressure Regulators, Relief Valves, Check Valves, Burst Disks, and Explosive Valves | | | | "Liquid Rocket Pressure Regulators, Relief Valves, Check Valves, Burst Disks, and Explosive Valves," NASA SP-8080, NASA, March 1973. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| NASA SP-8094 | Liquid Rocket Valve Components | | | | "Liquid Rocket Valve Components," NASA SP-8094, NASA, August 1973. |
| NASA TN D-7151 | Apollo Experience Report - Command and Service Module Reaction Control Systems | | | | Taeuber, R. J.; Weary, D. P.: "Apollo Experience Report - Command & Service Module Reaction Control Systems," NASA TN D-7151, NASA Manned Spacecraft Center, Houston, TX, June 1973. |
| NASA_TP_2012_217459 | Analysis and Derivation of Allocations for Fiber Contaminants in Liquid Bipropellant Systems | | Assessing the feasibility of allowing fiber particles that are larger than cleanliness level | | Lowrey, N. M.; Ibrahim, K.Y.: "Analysis & Derivation of Allocations for Fiber Contaminants in Liquid Bipropellant Systems," NASA_TP_2012_217459, Marshall Space Flight Center, Huntsville, AL, 2012. |
| RPL-TDR-64-25v1 | Aerospace Fluid Component Designers' Handbook Vol. 1 | | The "go-to" for component design | | "Aerospace Fluid Component Designers' Handbook Vol. 1," RPL-TDR-64-25v1, Air Force Rocket Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, Edwards, CA, February 1970. |
| RPL-TDR-64-25v2 | Aerospace Fluid Component Designers' Handbook Vol. 2 | | The "go-to" for component design | | "Aerospace Fluid Component Designers' Handbook Vol. 2," RPL-TDR-64-25v2,Air Force Rocket Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, Edwards, CA, February 1970. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| RPTSTD-8070-0001 | Surface Cleanliness Standard of Fluid Systems for Rocket Engine Test Facilities of the Nasa Rocket Propulsion Test Program | | | | "Surface Cleanliness Standard of Fluid Systems for Rocket Engine Test Facilities of the NASA Rocket Propulsion Test Program," RPTSTD-8070-0001, NASA, Washington D.C., October 2010. |
| SAE ARP 599 D | Dynamic Test Method for Determining the Relative Degree of Cleanliness of the Downstream Side of Filter Elements | | Not current as of June 2008 | | "Dynamic Test Method for Determining the Relative Degree of Cleanliness of the Downstream Side of Filter Elements," SAE ARP 599 D, SAE International, May 2002. |
| SAE ARP901 A | Bubble Point Test Method | | | | "Bubble Point Test Method," SAE ARP901 A, SAE International, May 2001. |
| SAE ARP901 B | Bubble Point Test Method | | | | "Bubble Point Test Method," SAE ARP901 B, SAE International |
| SAE J726 | Air Cleaner Test Code | | Canceled June 2002 | | "Air Cleaner Test Code," SAE J726, SAE International, June 1993. |
| SD-TR-84-34 | Particle Size Distribution on Surfaces in Clean Rooms | | | | Hamberg, O.; Shon, E. M.: "Particle Size Distribution on Surfaces in Clean Rooms," SD-TR-84-34, Vehicle Engineering Division, The Aerospace Corporation, El Segundo, CA, April 1984. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| SE_S_0073 G | Specification Fluid Procurement and Use Control | Specifies Final and Interface filters qualification in accordance with SE-F-044, test method per ARP-961 Bubble point, cleanliness ARP 599. | Levied by Shuttle Program on the vehicle and GSE. | Requires filters at the interfaces.<br>SN-C-0005 requires protection of components and system<br>NSTS 07700 3.6.12.1 says "Selection of system design shall include self-cleaning (filtering) protection compatible with component sensitivity | "Specification Fluid Procurement and Use Control," SE_S_0073 G, Johnson Space Center, Houston, Texas, May 1999. |
| SMC-S-005 | Space Flight Pressurized Systems | | | | "Space and Missile Systems Center Standard: Space Flight Pressurized Systems," SMC-S-005, Air Force Space Command, February 2015. |
| SN-C-0005D | Contamination Control Requirements | | | | "Space Shuttle - Contamination Control Requirements," SN-C-0005D, Johnson Space Center, July 1998. |
| SpacecraftContControl | Development of an Automated Optical Inspection System for Determining Percent Area Coverage for Spacecraft Contamination Control | | | | Hogue, P.; Coopersmith, J.: "Development of an Automated Optical Inspection System for Determining Percent Area Coverage for Spacecraft Contamination Control," Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland. |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| SPIE 4774 | Tailored particle distributions derived from MIL-STD-1246 | | | | Peterson, R.; Magallanes, P.; Rock, D.: "Tailored particle distributions derived from MIL-STD-1246," SPIE 4774,International Symposium on Optical Science and Technology, September 2002. |
| SPIE 995205 | Percent Area Coverage Through Image Analysis | | This is a Millipore document (from the web). This discusses Bubble point and other methods. Need to read in detail, but looks like it is aimed at very small micron rated filters. | | Wong, C.; Hong, S.; Liu, D.: "Percent Area Coverage Through Image Analysis," SPIE 995205, SPIE Optical Engineering and Applications, San Diego, CA, September 2016. |
| TB039 | Filter Integrity Test Methods | | Does not seem to have the detail necessary to be relevant for our systems. | | "Filter Integrity Test Methods," TB039, Millipore Corporation, 1999. |
| TO 00-25-223 | Integrated Pressure Systems and Components (portable and installed | | | | "Integrated Pressure Systems and Components (Portable And Installed) --Technical Manual," TO 00-25-223, U.S. Air Force, August 2017. |
| afspcman91-710v1 | Range Safety User Requirements Manual, Air Force Command Range Safety Policies and Procedures | Air Force Range Safety Requirements | | | |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| afspcman91-710v2 | Range User Launch Safety Requirements Manual, Volume 2, Flight Safety Requirements | Air Force Range Safety Requirements | For ground support, refers to KSC-C-123 or T.O. 42C-11, Cleaning and Inspection Procedures for Ballistic Missile Systems.<br>- discusses ground filters briefly<br>-discusses "Design Considerations for Addressing Contamination" in flight systems | | |
| afspcman91-710v3 | Range Safety User Requirements Manual Volume 3 – Launch vehicles, payloads, and ground support systems requirements | Air Force Range Safety Requirements | | | |
| afspcman91-710v4 | Range Safety User Requirements Manual, Airborne flight safety system design, test, and documentation requirements | Air Force Range Safety Requirements | | | |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| afspcman91-710v5 | Range Safety User Requirements Manual Volume 5 – Facilities, structures and reusable launch vehicle/reentry vehicle operating location requirements | Air Force Range Safety Requirements | | | |
| spcman91-710v6 | Range Safety User Requirements Manual Volume 6 – Ground and launch personnel, equipment, systems, and material operations safety requirements | Space Force Range Safety Requirements (replaces previous Air Force document) | Contains references for all volumes | | |
| spcman91-710v7 | Range Safety User Requirements Manual Volume 7 – Glossary of references, abbreviations and acronyms, and terms | Space Force Range Safety Requirements (replaces previous Air Force document) | Contains internal filter and mentions cleanliness levels | | |
| 73P620001 | Specification for High Pressure Solenoid Valve | Spec for Shuttle APS OMS high-pressure GHE valve | Contains internal filter and mentions cleanliness levels | | |
| 73P620004 | Specification for Low Pressure Solenoid Valve | Spec for Shuttle APS, PBK & OMS low-pressure GHE isolation valve | Contains internal filter and mentions cleanliness levels | | |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| 73P620002 | Specification for Series Redundant Helium Pressure Regulator | Spec for Shuttle APS & OMS GHe Regulator | Mentions cleanliness levels | | |
| 73P550013 | Specification for Propellant Tank | Spec for Shuttle OMS Propellant Tank | Contains internal filter and mentions cleanliness levels | | |
| MC284-0481 | Specification for Quad Check Valve | Spec for Shuttle OMS check valve | Contains internal filter and mentions cleanliness levels | | |
| MC276-0017 | Specification for High Pressure Helium Coupling | Spec for Shuttle high-pressure GHe and GN2 couplings | Contains internal filter and mentions cleanliness levels | | |
| MC276-0018 | Specification for Hypergolic Servicing Coupling | Spec for Shuttle hypergolic couplings | Mentions cleanliness levels | | |
| MC282-0061 | Specification for Reaction Control Propellant Tank | Spec for Shuttle RCS tank | Contains internal filter and mentions cleanliness levels | | |
| MC284-0419 | Specification for High Pressure Solenoid Valve | Spec for Shuttle RCS high-pressure GHe valve | Contains internal filter and mentions cleanliness levels | | |
| MC284-0420 | Specification for Low Pressure Solenoid Valve | Spec for Shuttle RCS low-pressure GHe valve | Contains internal filter and mentions cleanliness levels | | |
| MC284-0421 | Specification for pressure relief valve | Spec for Shuttle FRCS, ARCS, OMS & PRK relief valve | Contains internal filter and mentions cleanliness levels | | |
| MC467-0028 | Specification for Primary RCS Thruster Assembly | Spec for Shuttle RCS Primary Thruster Assembly | Contains internal filter and mentions cleanliness levels | | |

| Document Number | Title | Summary | Notes | Key Points | Citation |
|---|---|---|---|---|---|
| MC621-0009 | Specification for OMS Rocket Engine | Spec for Shuttle OMS Engine | Contains internal filter and mentions cleanliness levels | | |
| MC621-0059 | Specification for Aft Propulsion Subsystem | Spec for Shuttle Aft Propulsion System | Contains internal filter and mentions cleanliness levels | | |
| MC284-0604 | Specification for Torque Motor Latch Valve | Spec for Shuttle RCS latch valve. | Contains internal filter and mentions cleanliness levels | | |
| MC284-0430 | Specification for AC Motor Valve | Spec for Shuttle propulsion systems AC Motor Valve | Contains internal filter and mentions cleanliness levels | | |
| MC284-0623 | Specification for Pressure Relief Valve and Burst Disc | Spec for Shuttle BDRV for Orbiter Prop Transfer System | Summary of filters and cleanliness levels in RCS | | |
| RCS Blue Book | RCS Blue Book | Basic description of Shuttle RCS and components | | | |
| 80900200103 | Space Shuttle External Tank Propulsion Data Book, 80900200103, Propulsion Analysis Group, Lockheed Martin, January 2005 | | | | |

# Appendix B. Filtration and Contamination Terminology

Common terminology for filtration and contamination analysis is provided below:

**Boiling pressure test**: The boiling pressure test, often called “open bubble point” or “mean flow pore size” test, is an extension of the bubble point test and is used as a nondestructive method of measuring the average, or mean, pore size of a filter.

**Bubble point test**: A non-destructive means of determining the size of the largest pore in a porous medium.

**Cleanliness level**: Same as contamination level.

**Collapse pressure**: The maximum differential pressure which the filter element assembly must be able to withstand without collapse and continue to meet the filtration requirement.

a. This definition may differ from industry requirement definition or understanding.
b. May need to define filtration requirement expectations to specify performance characteristics.
c. May need to define how core support structure specification is communicated.

**Contamination tolerance** (holding capacity): The minimum weight of standard contaminant which can be added at the inlet of a filter under specified flow, fluid temperature and pressure conditions before the pressure loss exceeds a maximum allowable value.

a. *Holding capacity* is the more commonly used term.
b. Question on relevance/adequacy of definition. May be possible to define independently of other flow performance variables.

**Contaminant tolerance index**: The weight, in milligrams, of a specified particulate contaminant (e.g., AC Coarse Dust) which will cause a specified rise of pressure differential across one square inch of filter medium at a specified unit flow rate (GPM/in$^2$) of particular fluid. Needs updated dust specifications and rationale to use efficiently.

**Contaminant transmission rating**: The maximum particle size found in a fluid sample taken during contaminant tolerance tests. Cleanliness of working/test fluid is independent of added particulate.

**Contamination level**: A measure of the particulate contaminant found in a specified volume, usually 100 ml., of fluid sampled from a system at a specific time and location. Contamination levels can be expressed either in terms of quantity of particles in various size ranges, or gravimetrically in terms of milligrams. Occasionally, in determining contamination levels, a differentiation is also made by physical properties, chemical composition or particle shape. In addition, the amount of dissolved material or non-volatile residue (NVR) is often specified.

**Contamination tolerance level**: The maximum particle size, or the contamination level of a fluid system, which cannot be exceeded without affecting the specified performance, reliability or life expectancy of the components of the system.

**Depth filter**: A filter consisting of a porous material, or combination of materials, with long, often intricate, interstices which trap particulate contaminants within these flow paths.

**Dutch weave**: A weave wherein the shute wires are of a smaller diameter than the warp. The shute wires are driven up against each other. *Shute* may be replaced with *weft*.

**Filter**: Component designed to entrap expected contaminants in a system. Typically made up of two main parts, a filter element and a housing. However, some have only a filter element.

**Filter element**: The assembly of filter medium, support materials, and end fittings.

**Filter medium**: The porous material, or combination of materials, which are used to remove solids from a fluid stream. May also include the support structure

**Filter rating, absolute**: The size, in microns, of the largest hard spherical particle (i.e., glass beads) which would be removed by the filter.

**Filter rating, mean or average**: The size, in microns, of the average, or mean, pore diameter of a filter. This rating, though not in common usage, can be determined by various standard destructive and nondestructive tests, and is a good indication of the filter's ability to remove particles smaller than its absolute rating, as well as of the particle size to which the filter is most sensitive with respect to clogging.

**Filter rating, nominal**: Nominal ratings attempt to assess the ability of a filter to remove a specified percentage of particles which are smaller than the absolute rating by assigning a "nominal" rating value, which is smaller than the absolute rating. Note that the definition varies based on the organization.

**Filtered contamination level**: The cleanliness level of the fluid, as sampled at the outlet of a filter at rated flow and under conditions which simulate system operating conditions. The sample includes all fluid passed through the filter and all particulate matter regardless of source.

**Filtration efficiency**: Same as retention index.

**FOD screen**: Component that protects against unexpected contaminants and debris (e.g., the failure of a component internal to the flow system). FOD screens do not specify a holding capacity, only a micron rating and pressure drop at a target flow rate.

**Glass bead rating** (GBR): Same as absolute rating,

**GSE and facility filter**: "Roughing" filter of adequate surface area to remove gross amounts of contamination over long periods of operation with minimal service. This type of filter is generally larger than typical vehicle filters.

**Initial bubble point**: The air pressure, in inches of water, required to produce the first bubble in a liquid of known surface tension, in which the element is wetted, immersed to a known depth and pressurized with air. The bubble point test is a non-destructive method for verifying the maximum pore size of a filter medium and is presented in detail in SAE ARP 901 [ref. 27].

**Initial element cleanliness**: The cleanliness level of a new filter, or element, prior to installation as measured per ARP 599 [ref. 40].

**Inlet filter**: A small modular filter, frequently installed by component manufacturers at the inlet of components, or at test connections leading to the components, for the purpose of protecting the component from harmful contaminants with particular emphasis on the size distribution, rather than the quantity of contaminants to be encountered.

**Mass flow cycle**: The total throughput, in weight or volume of fluid, which will pass through a filter during a mission duty cycle, including check-out of the filter and system.

**Particle size**: The maximum linear dimension of the particle. [MIL-STD-1246C]

**Media migration or shedding**: The presence of particulate contaminant identifiable as filter material, or the supporting structure in the fluid which has passed through a filter.

**Non-volatile residue** (NVR): The residue remaining in an evaporated sample of filtered liquid. Generally expressed in milligrams per 100 milliliters of fluid.

**Plain Dutch single weave** (PDSW): A Dutch weave, also known as corduroy or basket weave, with relatively thick warp wires, spaced well apart, and with thinner shute wires passing over one-under one and driven together in a single layer. Light is transmitted at an angle to the face of the cloth. An easy cloth to clean with excellent flow characteristics.

**Plain square weave** (PSW): A square weave, wherein each shute wire passes over one warp and under the next. Ordinary household window screen is an example of PSW.

**Plain weave**: A weave in which the shute wires pass over one warp and under the next adjacent warp.

**Pressure drop (clean)**: The pressure differential across a clean filter unit including inlet and outlet ports under specified condition of flow rate, temperature, pressure and flow medium. SAE ARP 24 B [ref. 41] presents recommended methods in detail.

**Pressure drop at rated contaminant**: The pressure differential across a filter unit, including inlet and outlet ports, after a specified weight of a contaminant having a specified particle size distribution has been added on the inlet side of a filter, under specified condition of flow rate, temperature, pressure, and flow medium.

**Retention index**: The percentage of contaminant retained on or within a filter medium when a known amount of contaminant is injected upstream of the medium at a specified flow rate of a specified fluid. (See *filtration efficiency*)

**Reverse Dutch weave**: A weave wherein the shute wires are of a diameter larger than the warp. All shute wires are driven together.

**Screen**: See FOD screen

**Silting**: Silting is an accumulation of minute particles in the size range normally not counted, of sufficient quantity to cause haze or partial-to-complete obscuring of gridlines (or any portion of the grid) on a test filter membrane, when observed by the unaided eye or under 40-power magnification. The particles may range in size up to 5 microns.

**Square weave**: A weave in which the shute wires are separated from each other as they cross the warps so that a square opening is formed.

**Surface filter**: A filter which performs its filtering function by separating particulate contamination at the upstream surface of the media.

**System filter**: A “mass filter” installed by the system manufacturer for the purpose of reducing the total system fluid contaminant level input to a point where the component inlet filters can provide adequate protection at the interface to the critical operating components during the mission duty cycle of the system.

**Total contaminant input**: A gravimetric expression of the amount of particulate contamination entrained in a system fluid which flows through a filter or other components during a mass flow cycle. This value can be calculated empirically by multiplying the gravimetric contamination level by the total volume of fluid passing through the filter and dividing by the volume of the fluid sample upon which the contamination level was based. May also be called *contamination profile*.

**Total filterable solids**: The weight of material which can be filtered from a specified volume of fluid using a filter of specified size rating and type, generally 0.45 micron membrane type.

**Transmission index**: The ratio of maximum particle size of particulate which passes through a filter to the glass bead rating of the filter. The transmission index of a filter medium is related to the tortuosity of the flow paths through the medium.

**Twilled Dutch double weave** (TDDW): Also known as micronic cloth, it is essentially a twilled Dutch weave, wherein a double layer of shute wires is woven into the warp by offsetting the shutes. The flow path is quite tortuous, and the cloth is "light tight." The surface is smooth. There are twice as many shute wires of the same diameter as in PDSW. This weave has excellent control of glass bead filtration rating and is used for critical filtration applications. It is difficult to clean.

**Twilled Dutch single weave** (TDSW): A Dutch weave with a single layer of shute wires which overlap each other slightly. Each shute wire passes over two-under two. This weave is not as tight as PDSW and is not used where glass bead filtration rating is critical. It has excellent flow characteristics and will transmit light at an angle to the face of the cloth.

**Twilled square weave** (TSW): A square weave wherein each shute wire passes over two and under two warp wires. This weave is used when wire diameters are small to avoid the relatively sharp bends associated with over one-under one construction. Weaves finer than 250 x 250 are of twilled construction.

**Twilled weave**: A weave in which the shute wires pass over two consecutive warp wires, then under two consecutive warps.

**Unit flow rate**: The flow rate through a filter medium divided by the area of medium exposed to flow.

**Useful service life**: The time, in terms of volume of fluid or hours of system performance, before a filter develops a pressure differential due to contaminant build-up, which adversely affects the performance of an operating component of the system.

**Vehicle interface filter**: A final filter installed as an assembly with the ground half of a quick disconnect, or at the end of a flex hose, to control the cleanliness of fluids entering the vehicle during flushing, check-out, purging or loading operations. The major emphasis of this filter is placed on filter cleanliness, to assure fluid cleanliness reliability without the need for continuous monitoring or sampling.

**Warp wires**: The strands of a filter cloth set up in the loom prior to weaving the fill wires. The warp wires run the length of the finished screen.

# Appendix C. Vendor Survey Results [Portions Redacted]

1. **What are your greatest concerns and challenges with system filtration and/or filtration hardware?**
    a. <Redacted>
    b. <Redacted>
    c. <Redacted>
    d. <Redacted>
    e. <Redacted>
    f. <Redacted>
    g. <Redacted>
    h. <Redacted>
    i. <Redacted>
    j. <Redacted>
    k. <Redacted>
    l. <Redacted>
    m. <Redacted>

2. **What methods/guidelines do you currently use for system filtration and/or filtration components?**
    a. <Redacted>
    b. <Redacted>

c. <Redacted>

d. <Redacted>

e. <Redacted>

f. <Redacted>

g. <Redacted>

h. <Redacted>

i. <Redacted>

j. <Redacted>

k. <Redacted>

l. <Redacted>

m. <Redacted>
n. <Redacted>

o. <Redacted>

3. **Are there any lessons learned that can be shared?**
    a. ARP901 technically is valid only for Dutch twill weaves.
        i. Only <100 micron woven wire mesh is Dutch twill.
        ii. Correlation from filtration rating to bubble point is assumed to be equivalent for all Dutch twill weaves, but it's actually not.
        iii. Bubble point physics as assumed in ARP901 become unrealistically challenging on pores equal to larger than 300 micron.
    b. Filtration rating requirements often have little relationship to the actual size of harmful particles to a system.
        i. Typically generated by applying tighter and tighter filtration requirements to a system until FOD stops becoming an issue.
        ii. End users should not trust filtration ratings as realistic.
    c. Dirt capacity requirements are typically arbitrary and not understood. It is extremely valuable to show end users a volumetric example of 1 gram of dirt.
    d. Collapse pressure is often set as equal to full system pressure as a heritage requirement.
        i. Verification is typically lacking as it is difficult to create a porous filter element that has the same pressure boundary rating as the pressure vessel in which it resides.
        ii. Collapse requirements are typically driven by a desire to survive either a clogged condition or a transient condition.
        iii. Often poorly written and seldom verified as written but flowed down as a "shall" requirement.
    e. Issues with the end user relationship between amount of particulate and equivalent surface area blocked by particulate exist on requirements.
        i. Traceability for the relationship is seldom shown.
        ii. It is often not a realistic loading scenario—dirt doesn't load evenly.
        iii. Amount of blockage seems to be based on clean room documents that correlate surface area of a workspace that has X number of particles settle onto it during use of a clean room.
    f. Sintered woven wire mesh has a reputation of solving multiple issues without verification.
        i. NASA lesson learned is often cited for this assumption: https://llis.nasa.gov/lesson/471
        ii. Actual lesson learned states don't manufacture dirty filters, they will shed the dirt that you build them with. This somehow became non-sintered woven wire mesh sheds things.

g. Fundamental filtration methods are not understood.
    i. Surface vs. depth particulate removal, single pass vs. multi-pass methods, efficiency ratings vs. absolute, verification approaches, bubble point, challenge tests, etc.

h. Filtration rating has multiple definitions that are not typically understood by users.
    i. Absolute has multiple definitions. The filtration industry has warped this term to meet what they build – instead of only calling 100% absolute. Absolute could mean 100% (woven wire mesh min pore size), 97% (glass bead test), 99.X % (depth-based filter efficiency), etc.
    ii. Nominal – some arbitrary filtration efficiency of 90-98%, typically associated with the benefits of a filter cake developed during multi-pass use.
    iii. Geometric Pore Size – physical size of the hole in a surface media, which particles smaller than the hole will fit through
    iv. Particulate challenge data – actual test data of "calibrated dirt". Differs from pore size or glass bead test because particles are not spherical. Longest axis of a particle (when it's not a fiber) characterizes the particle size. Typically, particles 2.5x times the pore size will pass through a filter media.
    v. Glass bead data – closer to geometric pore size, calibrated glass beads that more repeatability characterize a pore size. Differs from a geometric pore size.
    vi. Bubble point – correlate test pressure required to push gas through a porous media. Higher pressure equals smaller pore.
    vii. All of these definitions are different and are often unique to each filter media type and grade. Relationships between definitions exist but are not consistent enough for a one size fits all correlation between them. For example, a chart from ASTM E2814 showing 4 different methods of calculating "filtration rating". All roughly agree but could present challenges when trying to verify "absolute" and creating a hard acceptance value.

i. Filter technical specifications should be displayed directly on the filter housing, especially MAWP.
    i. Obscure part numbers from out-of-business companies aren't helpful.
    ii. The printing should not be silk screen or electro-penciled, as it wears off over time.
    iii. Similarly, rivets on tags tend to rust out and then the tag is lost. Stamped lettering directly on the housing is the most durable.

j. Filter elements should be able to be separated from the housings and cleaned independently. They can then be reinstalled in the housing without removing the housing from the system. This is important when pipes and housings are welded in.

k. Many filters are oversized. Tube size inline filters and screens are much more convenient.

l. Filter housings and elements should be standardized across facilities, to minimize spares inventory and ensure that replacements are easy to find. Some larger filters designs share the same elements as smaller filters, they just use more of them.

m. Within individual designs, connections and components should reflect industry standards.

n. Consider the ergonomics of servicing when a filter is installed.

o. Ensure that housings have a small port for vacuum breaking and venting during removal and installation. This ports are also useful for purging the filter in and out.

p. For medium sized filters, where weight becomes a concern but sizes are still small enough that material strength is not the primary driver, (i.e., 1”, 2”) aluminum is a desirable material. There have not been any significant galvanic corrosion issues with aluminum filter housings even when connected to stainless tubing systems.

q. Resistance welding (used to join mesh screens) has proven difficult to inspect, especially with fine mesh screens, leading to filter failures when process controls have failed.

r. Use only compatible materials.

s. Throughout integration and test, flow fluid (no matter how little fluid) in inlet-to-outlet direction only.

t. Reuse is becoming common. Multiple mission use without removing the filter can tax the dirt capacity based on the Guernsey approach where components continue to shed particles over a long lifetime with many fluid loads.

u. Performing full system clogging analysis near the inception of the system development program is recommended to ensure filters are sized correctly to meet the systems requirements.

v. Witch hat filters appear to be much more effective in terms of holding capacity per unit flow area that even pleated filters.

w. Filter blockage due to particulate shedding from upstream components is much less meaningful than what is proposed in the existing literature (e.g., AIAA 92-3535). The long duration “particulate generation” models that exists in industry are incredibly conservative which also causes an issue in writing margins for reuse. It’s a cost/mass/time trade on if those models should be refined with testing or not but for applications typically coming up with a realistic particulate generation model will likely be worth it.

x. Filter capacity is just as important as filtration sizes and should be test verified early in development. Especially for reusable vehicles.

y. Design practice should ensure that filters are not placed immediately downstream of orifices, flow control valves, or other components that can produce a jet of fluid at the outlet of the component. This jet can cause local pressure overload of filter elements or dynamic excitation leading to filter fatigue failure. In cases where this arrangement must be made, extensive testing is required to ensure that the filter will survive the expected life across various allowed inlet conditions.

z. There are problems with debris generation from the filter itself due to remnants of fine weld spatter, etc., becoming dislodged in use. For small opening filters, this level/size of debris may be hazardous to downstream components.

aa. It is desirable to place a filter at the last possible location in the system to catch any particles generated upstream before they enter a downstream component. It is sometimes impractical to place a fine, high capacity filter at the interface to the next component. For example, a large propellant fill system filter capable of handling all propellant entering a vehicle will usually not be conducive to placement at the quick disconnect to the vehicle due to size and mass. In this case, it has often been found valuable to place an additional small but coarse filter at the interface location. Sometimes referred to as a “rock catcher” or “last chance filter,” these filters are not designed to provide the same sort of filtration level or capacity as the larger upstream filter, but they help prevent entrance of larger debris that could accidentally be introduced into the system, such as a tool, fastener, rag, insect, etc.

4. Is there any other system filtration or filtration hardware information that may relevant to our assessment?
    a. System filtration needs stem from a combination of the system cleanliness requirement, the size of the system (wetted surface area and volume), and the pressure drop allocation at the mission start and mission end. Ultimately, the size distribution and quantity of particulates in the operating system is what is important for sensitive components, like valves and regulators.
    b. Another challenge involves the verification of filter performance, given a set cleanliness level requirement. Typically, the dirt holding capacity of the filter is tested using a standardized “test dust.” This test dust (several are available) has its own set of typical size distribution of the particulate. These distributions tend to not align well with the cleanliness level distributions. Therefore, testing to the required limit in one size range often causes over testing in other size ranges.
    c. In general filtration science, requirements, expectations, vendors, technology, etc., has been stagnant since Apollo (maybe Shuttle). This can be attributed to “it’s just a filter”. The component itself is not as technically challenging or interesting as other components.
    d. Filter blockage due to particulate shedding from upstream components is much less meaningful than what is proposed in the existing literature. Additional studies characterizing the particle production behavior of components, tanks, and lines would benefit the industry in terms of reducing over-conservatism in filter sizing. Tests which directly assess filter blockage are preferable to tests that rely solely on effluent particulate count.
    e. Best practices:
        i. Periodic maintenance or DP monitoring of ground-side filters can prevent failures that contaminate flight hardware.
        ii. Where particulate is expected in the system (e.g., sooting, corrosion/reaction products), filters should be monitored with instrumentation or inspected to prevent unacceptable clogging or failure.
        iii. Part-mark filters with an arrow, even if symmetrical, to prevent inadvertent flipping of orientation during maintenance – and ejection of debris into the system.
        iv. Valve-level filtration, if required, should be factored into the design early, given the balance between flow area and protection that the filter provides. Retroactive filter implementation can be challenging.
        v. Filters on bidirectional systems (for example, fill/drain plumbing connecting a test stand to a rocket vehicle) should employ a filter bypass loop for drain back to prevent back flow of the vehicle fill filter.

# Appendix D. Lessons Learned

This appendix contains lessons learned from NASA programs and projects. The lessons learned are provided as individual items submitted from within the NASA community.

- Loose internal parts within a filter upon initial build were driven by a process escape at the vendor that led to improper shimming during the fabrication/assembly process.
    - The escape by screened by the acceptance test program (ATP) vibration plus subsequent roll testing, where unexpected motion of the loose parts was heard. Thus, ATP environmental testing is worth the effort even for something like a filter with no moving parts.
- Collapse of valve inlet filter elements due to excessive pressure drop ($\Delta$P).
    - The collapse was driven by unanticipated/underestimated surge flow during system activation/priming/water hammer events. Comprehensive analysis and flight-representative testing is needed to accurately estimate the max delta P and time of exposure for inclusion in a filter specification. A $\Delta$P proof test across the filter element itself (vs. the housing) should also be considered to verify adequate structural integrity of the design (part of qualification testing) and to screen for workmanship defects on individual units (part of acceptance testing).
- Excessive particulate contamination in delivered valve inlet filters that had been verified as clean.
    - This issue was driven by ineffective cleaning methods and final cleanliness verification using low pressure gas flow (vs. liquid) at the vendor. Ultrasonic cleaning, random vibe, and liquid (vs. gas) cleanliness verification were subsequently implemented for all filters upon receipt to remove unexpected contamination prior to assembly/integration into the next higher assembly.
- Corrosion-resistant steel filter mesh and titanium (Ti) etched disk filter elements have proven susceptible to Ti particle impact ignition in a $GHe/GN_2$ pressurant plus nitrogen tetroxide (NTO) vapor mixture, single-phase NTO liquid, and a two-phase NTO liquid/vapor environment at very modest pressure/temperature conditions and relatively low velocities
    - A dedicated assessment of enveloping particle sizes/quantities, maximum impact velocities, and possibly some particle impact ignition testing is needed to verify a low/no risk posture prior to usage in a flight or ground test system (same for pure $GO_2$ and mixtures containing significant quantities of $GO_2$).
- Filters became loaded with Krytox/Braycote and eventually allowed some of that fluorinated lubricant to pass through to sensitive components downstream (e.g., hydrazine thruster catalyst beds).
    - This was caused by excessive use of Krytox/Braycote during fabrication and assembly/integration of upstream system hardware and the need for technician training. and process controls to preclude excessive lubricant as a possible threat.
- Excess particulate can be introduced into a flight prop system during system assembly/integration in a clean room environment.
    - This was caused by a non-standard clean room configuration (e.g., no roof, horizontal air flow), too many people and unrelated operations in close proximity to an open prop

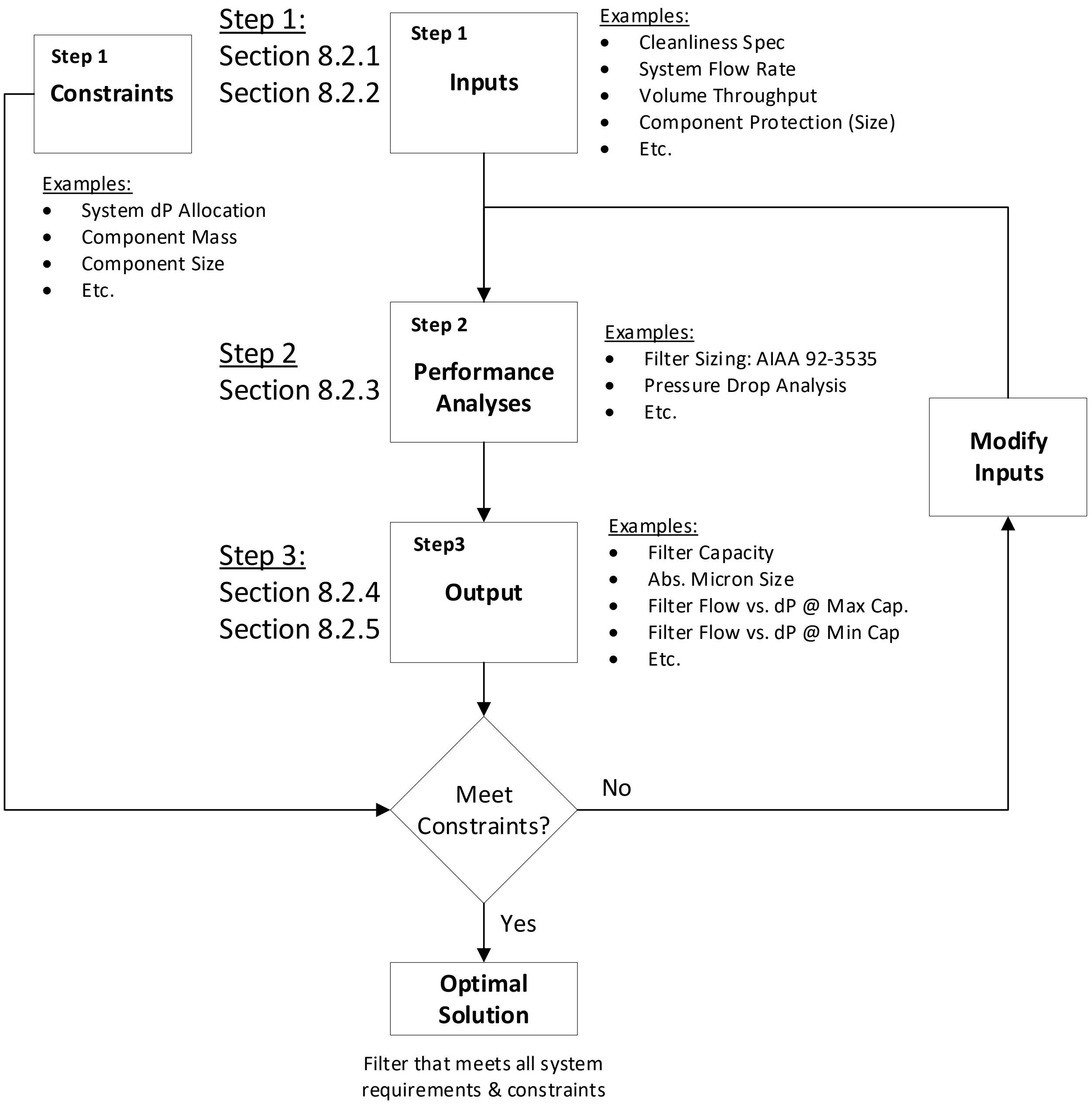
  - system within the clean room, ineffective cleaning of tubing segments at an off-site clean house, and contaminated GSE suppling an argon purge to the prop system during welding. Fixes involved tightening up on clean room ops, fixing the contamination issues for the tubing and argon supply, flushing as much of the integrated prop system as possible to remove and characterize excess contamination, and relying on filter capacity analysis (backed-up by solid test data at component level) to demonstrate acceptability for a single flight.
- There was potential for contamination of a flight prop system during commodity loading due to contaminated GSE.
  - This condition was enabled by having GSE final filters and prop sample ports located some distance upstream of the physical interface to the vehicle. This is why there is typically a requirement for a true interface filter at the connection point between the GSE and the flight vehicle.
- Needle bearings from an 8-in. $LO_2$ fill/drain valve unexpectedly released as macro-sized FOD into the Shuttle MPS cryogenic propulsion system during ground testing of the integrated system Main Propulsion Test Article.
  - This condition was driven by design-related issues and unrecognized cycle count limitations that led to mechanical failure of the hardware. One part of the corrective action involved installing “rock catcher” screens at the inlet to all MPS pre-valves to avoid a potentially catastrophic failure of a running Space Shuttle Main Engine (SSME) from ingestion of FOD if the issue ever recurred during terminal count or during flight.
  - Note that post-flight inspection of all pre-valve screens became an every-flight requirement to identify and characterize the size, quantity, and nature of any debris that was present. FOD removal was usually attempted and successful but some particles couldn’t be retrieved and others were actually lost into the system during the attempt. Flight rationale depended on evaluating all particles remaining in the system for acceptability based on estimated size, quantity, and material from the inspection images.
- Ambiguity with the filter configuration on propellant valves in a flight propulsion system.
  - There was considerable discussion/debate during the early design phase regarding inlet-only vs. inlet and outlet filters on a motor-driven propellant valve used for manifold isolation (normally open, unidirectional flow) and a crossover function (normally closed, contingency cross feed, bidirectional flow). It was decided to implement an inlet-only filter config for the isolation valve and inlet and outlet filters config for the crossover valve which is consistent with JSC-08080-2B, standard F-29.
- Other generally related topics:
  - The need for inlet filters on each component tends to be challenged and heavily debated when the system delta P budget becomes a problem.
  - It is often difficult to get a solid explanation from a component vendor on their technical rationale for the absolute/nominal rating of an inlet filter intended to guard against the detrimental effects of contamination on the actuation and sealing functions of their hardware.
  - Having actual flow/delta P test data for a filter as a function of “dirt” load can be critically important when evaluating the impact of a contamination control process escape.

- There is rarely testing for partial clogging of filters. This should be performed on a regular basis.
- Filters on both inlet and outlet of a valve appears to be a good solution unless you start generating contamination (or build it in) that affects valve function more than it does the system. In this cases there is no way to flush out the contamination.
- During the Shuttle program a $LO_2$ facility probe broke off and jammed between a pre-valve and an added screen, preventing the pre-valve from closing. The fix was to add a “rock catcher” (0.125-in. holes) at the T-0 panel used for loading the vehicle with propellants. There was a tent constructed to change out this large (12-in., metallic) final $LH_2$ filter on the mobile launcher. It was a 70-micron filter which looked great on a schematic, but changing it required crane support and significant potential for introduction of debris downstream of the filter since the “valve skid” was full of peeling paint and environmental debris.
- When procuring a filter or component that contains a filter, specifically add a requirement to perform a filter dirt capacity and flow test using ISO test dust.
- When filters are required to be located internal to other components, such as solenoid valve, for performance of component (where particle contamination could create seat leakage, etc.) extreme care must be taken in cleaning the component before closeout or resultant component seat leakage may result.
- Dual filter directional is a significant challenge.
- Pay attention to the frequency of filter inspections or monitoring to head off issues.
- Always check the filter media that is for possible unexpected implications.
- Systems and components were improperly cleaned by an outside vendor. White powder residue (cleaning solution residue) was found in pneumatic tubes.
- An improper bubble point procedure accepted rejectable components.
- A filter supplier did not disclose a use-as-is part to a launch provider.
- There was damage to filter elements during production or operation. Receiving inspections are important.
- There was excessive lube on an element surface or silting. It resulted in flow restrictions and high $\Delta P$.
- An incorrect filtration was set up for tank wash allowing chlorinated city water into stainless tanks (Centaur). It was suspected of causing hydrogen embrittlement due to exposure to chlorides and moisture over time. The Centaur was de-erected at launch site and sent back to factory. The tanks were scrapped.
- Differential pressure, $\Delta P$, in the filtration wire-cloth of a filter is generally much less than the dP for the entire filter because the pressure losses due to flow direction turns and cross-section flow area changes in the filter housing and element are dominant. The same is sometimes true, but to a lesser extent, for screen assemblies. However, as the wire-cloth accumulates contaminant its $\Delta P$ does increase, but this increase often only becomes detectable when the contaminant buildup is often at/near a point where the wire-cloth can be severely damaged, breached, or destroyed.
- In generic terms, filters should be installed immediately downstream of all interfaces, including at test points or vents, where control of particulate matter is critical and at other

appropriate points as required to control particulate migration. All pressure systems should have fluid filters in the system, designed and located to reduce the flow of contaminant particles to a safe minimum.

- Best practice examples include verifying the cleanliness of flex hoses in the vertical orientation and for tube diameters equal to or greater than one inch. Verification of precision cleanliness should be performed by sampling a rinse fluid applied internally through use of a high-pressure nozzle to the entire length of the flex hose. For flex hose tube diameters less than one inch, the use of a high-pressure nozzle is preferred, but verification may be performed by flushing a rinse fluid through the entire length of the flex hose with agitation. Precision cleaning can be considered successful when the verification rinse fluid indicates compliance with the flex hose engineering drawing cleanliness requirement.
- Interface filters should not enable bypass flow and interface filters are required on outlet lines if it is determined that some operations, such as servicing or de-servicing fluids, could permit flow in a reverse direction.
- Properly sized filters eliminate the need for redundant (failure tolerant) filters.
- Conservatively sized propulsion system filters should be used immediately downstream of diaphragm propellant tanks in order to accommodate particulate levels which may exceed the specification levied on the tank.
- Clean propulsion hardware should be left in protective bagging unless it is necessary to remove it and that hardware should be tagged if it is exposed to an uncontrolled, non-cleanroom, environment.
- Both molecular contamination (e.g., the result of internal vapor mixing) and particulate contamination should be considered.

# Appendix E. System Filtration Design Process



# Appendix F. Step-by-step Filtration System Design Process

## Step 1. List of individual elements upstream of the filter

The region of interest includes all units and sub-assemblies (termed “elements”) that are upstream of the filter being assessed.

The list is intended to include the highest-level assembly that was verified clean to a specification. If a unit was cleaned to a specification and then integrated without further verified cleaning, then that unit is listed along with the specification used. If a unit is combined with other units/elements and then cleaned to a specification, list that final sub-assembly and that specification.

Group elements cleaned to a “per fluid volume” verification separate from any that may have been cleaned to a “per surface area” verification. To elaborate, IEST-STD-CC1246 includes the same specified number of particles of a given size range whether the count is taken “per 100 mL” or “per 0.1 $m^2$”. The intent associated with that commonality is that fluid cleaning of a surface should use a rinse amount of 100 mL per 0.1 $m^2$ of surface to be verified clean to the specification. For the dirt holding capacity analysis, however, the cleanliness specification listed should match the verification method for the element. If the number of particles of a given size range is calculated by taking the total mL of effluent and dividing by 100, the verification is against # per 100 mL (i.e., per fluid volume) and must remain so for the dirt capacity analysis. If the number of particles of a given size range is calculated using the internal surface area – so that the allowed count varies dependent upon the internal surface of the part – then the # per 0.1 $m^2$ is utilized for the analysis. There are no known instances of propulsion equipment utilizing a # per 0.1 $m^2$ verification. That would require, for example, that the cleaning of a line have a different allowed count per size range based on the length of the line. As such, while a per surface area approach is allowed by IEST-STD-CC1246, use of a per volume approach is recommended.

Individually cleaned lines should be included in the list. If the count of individual lines is not known, assume a worst-case condition such as assuming individual lines exist between every unit within the system.

Units and lines on dead-ended flow paths should be included for conservatism. While flow may not go through these elements, some amount of flow could go in/out and contribute to the particles going into a filter.

Elements that are utilized for the propellant loading (e.g., service valve and lines to the tank) should be counted twice since the total flow goes through these elements upon loading and will then go back through during mission life.

Welds between individual elements should be included on the list. Normal welds should assume a certain cleanliness specification (e.g., Level 25).

The fluid loaded into the system for flight (e.g., propellant) will also have an allowed particle count per size range. This can be thought of as the particulate picked up by upon flow through ground support equipment cleaned to a specific level. The fluid particulate will be a # per 100 mL value.

Aspects that add particulate as a one-time event (i.e., not on a per fluid volume basis) like weld repair or pyrovalve actuation should be included but grouped separately from the elements verified to a per-fluid-volume basis.

Utilize a format similar to that shown below. Select particle size ranges (aka “bins”) that match the cleanliness specifications used for the individual elements.

| | Specification allowed particle count per size range per 100 mL | | | | |
|---|---|---|---|---|---|
| | 5 to 10 μm | 10 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| Element name | | | | | |
| Element name | | | | | |

| | Specification allowed particle count per size range per 100 mL | | | | |
|---|---|---|---|---|---|
| | 5 to 15 μm | 15 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| Element name | | | | | |
| Element name | | | | | |

The grouping as shown above for the per-fluid-volume verification should be separate from a grouping of per-surface area and a grouping of particle count per “instance” (e.g., pyrovalve actuation or weld repair activity).

| | Specification allowed particle count per size range per 0.1 $m^2$ | | | | |
|---|---|---|---|---|---|
| | 5 to 15 μm | 15 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| Element name | | | | | |
| Element name | | | | | |

| | Specification allowed particle count per instance | | | | |
|---|---|---|---|---|---|
| | 5 to 15 μm | 15 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| Element name | | | | | |
| Element name | | | | | |

**Step 2. Multiplying factor for lifetime**

While totals across similar components can be performed, that approach complicates multiplication with the load fraction.

For all of the elements verified to a per-fluid-volume basis, the multiplying factor is the total fluid that will flow through the element listed. To maintain the correct “per 100 mL” basis of the factor, utilize the total fluid in mL divided by 100. If there is a flow split in the system, assess the amount of fluid that may go through each separate path.

| | Specification allowed particle count per size range per 100 mL | | | | | Total Fluid |
|---|---|---|---|---|---|---|
| | 5 to 15 μm | 15 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm | mL / 100 |
| Element name | | | | | | |
| Element name | | | | | | |

If there are elements verified on a per-surface-area basis, the multiplying factor is the number of times the fluid next to that surface area is cycled / replaced. This number should be a function of the internal volume of that element. That is, in order for fluid to be in contact with the interior surface of the element, the element must be “full” of fluid; every time that quantity is removed and replaced, the interior surface area contributes the specified allowance. The total fluid divided by the internal volume of the element is the number of cycles that the surface area contributes particulate.

|  | Specification allowed particle count per size range per 0.1 m$^2$ |  |  |  |  | Total Cycles |
|---|---|---|---|---|---|---|
|  | 5 to 15 µm | 15 to 25 µm | 25 to 50 µm | 50 to 100 µm | 100 to 200 µm | total / unit vol |
| Element name |  |  |  |  |  |  |
| Element name |  |  |  |  |  |  |

For all counts per instance, like pyrovalve actuation and weld repair activities, the multiplying factor is the number of instances for that activity.

|  | Specification allowed particle count per instance |  |  |  |  | Instances |
|---|---|---|---|---|---|---|
|  | 5 to 15 µm | 15 to 25 µm | 25 to 50 µm | 50 to 100 µm | 100 to 200 µm | # |
| Element name |  |  |  |  |  |  |
| Element name |  |  |  |  |  |  |

Examples of pyrovalve actuation counts and weld repair counts are shown below. These counts are provided in size ranges consistent with IEST specifications as well as common NASA specifications. The intent is to utilize the size ranges that match the specifications of other elements within the given system.

| Specification allowed particle count per instance |  |  |  |  |  |
|---|---|---|---|---|---|
|  | 5 to 15 µm | 15 to 25 µm | 25 to 50 µm | 50 to 100 µm | 100 to 200 µm |
| 3/8" Pyro actuation | 1703 | 429 | 288 | 100 | 34 |
| 3/4" Pyro actuation | 8742 | 1854 | 1068 | 299 | 75 |
| Weld Repair | 600 | 120 | 30 | 8 | 4 |

| Specification allowed particle count per instance |  |  |  |  |  |
|---|---|---|---|---|---|
|  | 5 to 10 µm | 10 to 25 µm | 25 to 50 µm | 50 to 100 µm | 100 to 200 µm |
| 3/8" Pyro actuation | 1192 | 941 | 288 | 100 | 34 |
| 3/4" Pyro actuation | 6298 | 4298 | 1068 | 299 | 75 |
| Weld Repair | 450 | 270 | 30 | 8 | 4 |

If further conversion is necessary, the assumed fit is based on log$^2$ vs log. Each size range is converted to a particle count of X size and larger. In the IEST-style specification, this would mean 5+ microns, 15+ microns, etc. The log$^2$ is taken of these values (5, 15, etc.). The log is taken of the total count for these groupings. A linear fit is assumed to interpolate as required.

### Step 3. Particle decay rate

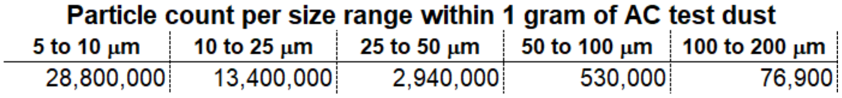
Repeated flushing of an element will result in a general trend of a decreasing particle count within each size range. JPL conducted tests of a 1 m section of ¼" line with around 1300 L of total fluid flushed to attempt to quantify that rate of decay. This limited test, however, is considered insufficient for wider application (i.e., the decay of many units may be quite different than the unit tested and the relevant dependencies were not determine). By not including a decaying rate, there will be some increase in the degree of conservatism of the calculation which may be taken into account when applying additional margin.

### Step 4. Total particle counts

Use the multiplying factor determined in Step 2 on each size range. The result is the count of particles throughout the mission usage from each element. A total across elements then provides the total count within each size range.

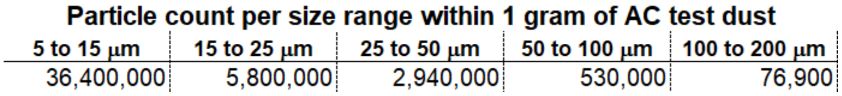
### Step 5. Conversion to test dust

JPL determined a correlation for the number of particles within each size range for a mass of ACCTD. The assumption is made that ISO dust remains similar to the prior ACCTD for this calculation. The particle counts are shown in the original size ranges from the JPL paper as well as for IEST size ranges.



**Particle count per size range within 1 gram of AC test dust**

| 5 to 10 μm | 10 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
|---|---|---|---|---|
| 28,800,000 | 13,400,000 | 2,940,000 | 530,000 | 76,900 |



**Particle count per size range within 1 gram of AC test dust**

| 5 to 15 μm | 15 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
|---|---|---|---|---|
| 36,400,000 | 5,800,000 | 2,940,000 | 530,000 | 76,900 |

To be clear, the particle count within a size range is not equal to 1 gram of ACCTD. Instead, 1 gram of ACCTD will have that many particles in each of the size ranges shown.

The total particle count within each size range from Step 4 is divided by the count shown above for the same size range. This will yield the grams of ACCTD needed to have an equivalent number of particles. The quantity of ACCTD needed to match the size range tends to be larger for the lower size ranges. This result is due to a slightly different distribution of particles in ACCTD as compared to IEST distribution assumptions.

### Step 6. Needed dirt holding capacity

A filter will trap particles below the absolute filter rating. The degree is estimated at half the absolute rating for this analysis. That is, a filter is assumed to catch particles down to half the absolute rating. The size range within which that half-rating falls should be included when assessing the dirt holding capacity. If the calculation is being conducted for a filter following an upstream filter, the conservative approach is to assume that the upstream filter only blocks particles of the absolute rating and not smaller.

The needed dirt holding capacity of the filter is the largest mass value across the appropriate size ranges. For example, if a 40-micron absolute filter is being assessed, the lowest size range included in the analysis is 15-25 (or 10 to 25) as half of 40 is 20. The lower size range (5 to 15 or 5 to 10) is ignored.

### Step 7. Margin

Margin is typically applied to the value from Step 5. Factors of 2x to 4x are typical. The resulting value is the requirement for a filter in the system assessed. That is, the filter should have a dirt holding capacity that meets or exceeds the calculated value without resulting in a pressure drop exceeding system requirements.

# Appendix G. Example System

The example system is shown in Figures G-1 and G-2.

The first step is to identify and label all system elements upstream of the filter, including lines and fittings. These items represent the sources of built-in contamination (see Section 8.1.1). Assign cleanliness levels to each element. If component or piece-part specifications are available, use the cleanliness levels provided therein. In the example below, the tanks, service valves, and pyrovalve are cleaned to particulate cleanliness level (PCL) 100 with the caveat that no particles above 50 microns are allowed. Cleanliness specifications for lines, fittings, and other piece-parts such as the venturi (V-1) are not known and are assumed to be clean to PCL 50.

Contamination due to system assembly is addressed by counting the welds and mechanical fittings (see Section 8.1.2). For this example, as in many systems to be analyzed, the actual number of connections (welds or fittings) is not known, and the assumption is used that one is located at each joint between adjacent system elements. Weld and mechanical fitting cleanliness data is further assumed to be unavailable for this system, so a cleanliness level of PCL 25 is assigned to each one. In addition to the particulate from standard welding during assembly, there may be repairs done which can add additional contaminant. If a specification exists, that allowed particle level should be included. For this example, a single weld repair operation is assumed matching the one-time particle increase of Table 8-1.3.

To calculate particulate loaded with the media (per 8.1.3), it is assumed a full propellant tank is 0.967 L and that the hydrazine propellant cleanliness is PCL 100 which allows 1185 particles within the 5-10 micron range per 100 mL. Calculations are based on a last-chance GSE filter rated to 10 microns. Under these conditions, the total estimated number of 5-10 micron particles that would be added to the system with the fluid is 11,459. The GSE filter catches all particulate larger than 10 microns, so no other size ranges are affected. During loading, propellant flows through some elements, like the service valve HOV-2, that are not otherwise flowed through during the mission. HOV-2 is thus counted within the unit listing (as is line TIL-3). A portion of line TIL-2 (TIL-2a) will be flowed through during loading and then back out during the mission. This effect is accounted for within the load fraction (which doubles the count).

Elements that are not truly flowed through during mission operations may be either excluded from the list or included for conservatism. For example, the service valve HOV-3 and line TIL-5 are utilized (flowed through) during ground test but not in flight. Including a particulate count contribution may be warranted if test fluids flowing through these elements during ground operations are expected to have added to the particulate within the system. The pressure transducer is similar in that the tube stub is dead-ended. Inclusion of the pressure transducer may be warranted to account for potential shedding despite flow not fully going “through” the unit.

Finally, self-generated contamination from within the system must be addressed. In this example, the only source of self-generated contamination that would be included in the filter capacity analysis is the actuation of the pyrovalve (PV-1). Ideally, data on the number and distribution of particles generated by the particular model of pyrovalve for this system would be used in the analysis. In practice, that type of data is rarely available. Instead, the values from Table G-1 will be used. Unlike the other sources of particulate that scale with volume throughput, the pyrovalve contribution is assumed to be a one-time event that adds a fixed number of particles, regardless of throughput.

*Table G-1. IEST-STD-CC1246 Particulate Counts With Revised Bin Size Limits*

| | 5-10 mm | 10-25 mm | 25-50 mm | 50-100 mm | >100 mm |
|---|---|---|---|---|---|
| PCL 100 | 1185 | 521 | 67 | 9 | 1 |
| Modified PCL 100 | 1185 | 521 | 67 | 0 | 0 |
| PCL 50 | 110 | 48 | 6 | 1 | 0 |
| PCL 25 | 15 | 6 | 1 | 0 | 0 |

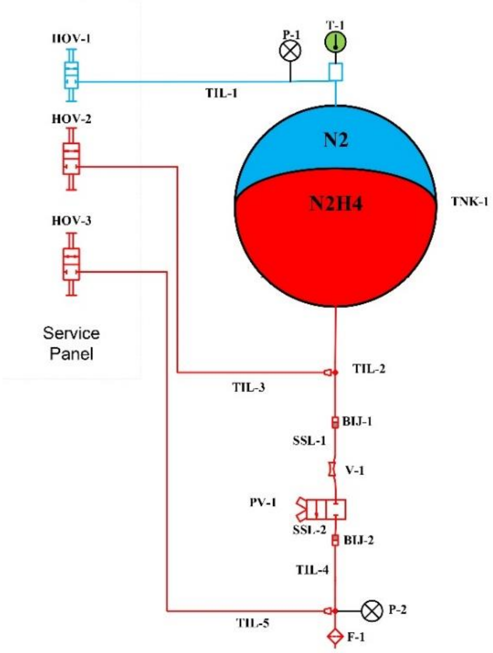


*Figure G-1. Example Problem Schematic Showing Labeled Lines and Fittings*

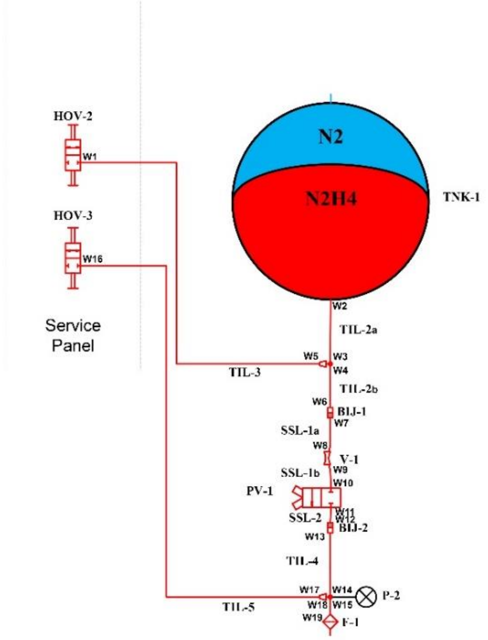


*Figure G-2. Example Problem Schematic Showing Labeled Welds*

List all system elements and welds in a table. Input the fraction of throughput, which can be found by dividing the volume of flow seen by the element by the total system volume. This will be 1 (100%) for items that see the entire volume of the system once. For items that are exposed on initial propellant loading as well as in mission operation such as a portion of line TIL-2 between the service valve HOV-2 and the tank, the fraction of throughput will be 2 (200%). If there were any parallel paths, the fraction would be the reciprocal of the number of paths (e.g., one-third for the case of three parallel paths).

Identify the filter split fraction. This is to indicate flow splits downstream of the system element which feed separate filters. It is equal to 1 divided by the number of downstream filter splits. In the current example, this will be equal to 1—as all elements feed a single filter. The overall load fraction for each element is the fraction of throughput multiplied by the filter split fraction.

For one-time events (e.g., pyrovalve actuation), the total particle count contribution is the particulate contribution multiplied by the load fraction (1 or 100% in this example). For the lines and other components, the total particle count contribution is the cleanliness particle count multiplied by the load fraction (1 or 100% for all components other than line section TIL-2a which is 200%) and then multiplied by the propellant volume. This latter volume must be placed in correct units as the particle count basis is per 100 mL. As such, the 0.967 L example results in multiplication by 9.67.

Determine the total particle count across the lifetime within each bin range. Last, convert the number of particles for each bin to mass of standard test dust using the values based on ACCTD and shown in Table G-2. Locate the bin which reflects the maximum amount of ACCTD, and use that mass as the filter design capacity (excluding safety factor). Note that a typical stacked etched-disk filter traps particles down to half its micron rating; particles smaller than this can be ignored under most circumstances. (Reference 16 discusses situations in which it may be prudent to consider particle size ranges slightly below one-half of the filter micron rating.)

Finally, apply an appropriate margin value consistent with the system design approach. A value of 2x is shown. The final value indicates a needed filter dirt holding capacity of 6 mg.

***Table G-2. Mass of Standard Test Dust Using Values Based on AC Coarse Test Dust***

| Individually-cleaned Component | Quantity | | Cleanliness Spec (# per 100 mL per size range) | | | | | | Fraction of Throughput | | Filter Split | | Total Load = mL/100 | | Lifetime Count per size range | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 5 to 10 μm | 10 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm | | | | | | | | 5 to 10 μm | 10 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm |
| Tank (TNK-1) | 1 | X | 1,185 | 521 | 67 | 0 | 0 | X | 100% | X | 100% | X | 9.67 | = | 11,459 | 5,038 | 648 | 0 | 0 |
| Line TIL-2a | 1 | | 110 | 48 | 6 | 1 | 0 | | 200% | | 100% | | | | 2,127 | 928 | 116 | 19 | 0 |
| Line TIL-3 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Fill valve HOV-2 | 1 | | 1,185 | 521 | 67 | 0 | 0 | | 100% | | 100% | | | | 11,459 | 5,038 | 648 | 0 | 0 |
| Line TIL-2b | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Bimetallic BIJ-1 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Line SSL-1a | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Venturi V-1 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Line SSL-1b | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Pyrovalve PV-1 | 1 | | 1,185 | 521 | 67 | 0 | 0 | | 100% | | 100% | | | | 11,459 | 5,038 | 648 | 0 | 0 |
| Line SSL-2 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Bimetallic BIJ-2 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Line TIL-4 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Transducer P-2 | 1 | | 1,185 | 521 | 67 | 0 | 0 | | 100% | | 100% | | | | 11,459 | 5,038 | 648 | 0 | 0 |
| Line TIL-5 | 1 | | 110 | 48 | 6 | 1 | 0 | | 100% | | 100% | | | | 1,064 | 464 | 58 | 10 | 0 |
| Fill valve HOV-3 | 1 | | 1,185 | 521 | 67 | 0 | 0 | | 100% | | 100% | | | | 11,459 | 5,038 | 648 | 0 | 0 |
| Welds (W1-W19) | 19 | | 15 | 6 | 1 | 0 | 0 | | 100% | | 100% | | | | 2,756 | 1,102 | 184 | 0 | 0 |

| Events | Quantity | | Allowance (# per size range) | | | | | Fraction of Throughput | Filter Split | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 5 to 10 μm | 10 to 25 μm | 25 to 50 μm | 50 to 100 μm | 100 to 200 μm | | | | | | | | |
| Propellant Input | 1 | X | 11,459 | 0 | 0 | 0 | 0 | 100% | 100% | = | 11,459 | 0 | 0 | 0 | 0 |
| Weld Repair | 1 | | 448 | 272 | 30 | 8 | 4 | 100% | 100% | | 448 | 272 | 30 | 8 | 4 |
| Pyrovalve Actuation | 1 | | 1191.580193 | 941.0813555 | 287.9954689 | 100.2102372 | 34.26312032 | 100% | 100% | | 1,192 | 941 | 288 | 100 | 34 |

| | | | | | |
|---|---|---|---|---|---|
| **TOTAL COUNT** | 85,914 | 33,076 | 4,437 | 224 | 38 |
| **Divide by:** Test Dust # per gram | 28,800,000 | 13,400,000 | 2,940,000 | 530,000 | 76,900 |
| | 0.003 | 0.002 | 0.002 | 0.000 | 0.000 |

0.003 grams (maximum value of entrapped bin ranges)

**Margin factor on analysis** 2x

**Equivalent test dust mass** = 0.006 grams

# Appendix H. Chemical Incompatibilities

Chemical incompatibilities between materials of construction and fluids within the systems have been shown to lead to corrosion [refs. 42, 43] that can move downstream and harm components. Chemical incompatibilities within operational fluids and changing environmental conditions have led to precipitate generation and subsequent failure of systems [ref. 44]. Prevention is the primary mitigation for self-generated contamination due to chemical incompatibility and guidance is provided for selecting materials to minimize this type of contamination [ref. 45]. However, no guidance is provided to quantify potential corrosion particulate generation.

Contaminant contributions from corrosion and precipitation should be included in filtration design and methods to characterize contaminant contributions from these sources and to generate a system-level contaminant contribution profile are described below.

## 1. Chemical Incompatibility: Corrosion

The following steps for determining the corrosion particulate generation rate by test should be considered:

a) Set up specimen per ASTM G1-03 "Standard Practice for Preparing, Cleaning, and Evaluation Corrosion Test Specimens" Sections 5 and 6 [ref. 46], or similar

b) Run corrosion testing per appropriate method specific to the application including considerations such as stagnant vs flow conditions, materials of construction, working fluids, exposure environments, etc. The American Society for Testing and Materials provides a wide range of applicable standards for this purpose.

c) Measure corrosion rate (change in mass of the material as a function of time), corrosion displacement rate (mass of material going into the working fluid as a function of time) and characterization of displaced corrosion (particle size distribution). In the absence of corrosion displacement rate data, a conservative approach would be to assume that all generated corrosion material is displaced and should be mitigated in filtration design.
   - Plot the number of corrosion particles displaced (pdc) vs time for each bin size (n): (pdc-1, pdc-2, …pdc-n).
   - Curve fit the data to get an equation for particles (of a given size) as a function of time.
   - Determine the duration of operation of the system (top).
   - Use the equation to calculate total quantity of particles generated over operational lifetime per bin size.

## 2. Chemical Incompatibility: Precipitation

Determining the contamination profile of precipitation can be determined by test or analysis. Both approaches require an understanding of the chemical composition of all fluids. Specifically, it is necessary to understand the ions that can exist based on fluid chemistry and contamination sources (e.g., leaching from materials, fabrication materials). Chemical composition of liquids can be determined using a number of standard methods including ion chromatography, liquid chromatography-mass spectrometry (LC-MS), Raman spectroscopy, Fourier-transform infrared spectroscopy (FTIR), and High Performance Liquid Chromatography (HPLC), among others. Once the basic chemical analysis is complete, the quantity of precipitation may be determined experimentally, with the added benefit of an opportunity to determine particle size distribution, or analytically, with the added benefit of significant cost savings.

Empirical approaches to evaluate precipitation involve traditional laboratory chemistry processes and procedures to calculate the anticipated quantity of precipitate formation in a system. Similarly, traditional microscopy can be used to characterize the size distribution of precipitates that are generated empirically. Analytic estimates of precipitation quantities involve basic chemical analysis found in a variety of general chemistry textbooks and can provide a reasonable estimate of total particulates generated in a closed system. These methods are described below. Analytical methods also exist for estimating size distribution, but are significantly more complex than for quantification, as most precipitates are salts that form via crystallization, and will not be discussed here [ref. 47].

### Reaction-Induced Precipitation

The combination of solutions can result in a chemical reaction followed by precipitate formation depending on the temperature, pH, and concentration of ions in solution. Solubilities of molecules in aqueous solutions can be found in CRC Handbook of Chemistry and Physics [ref. 48] at specified temperatures and solutions as well as in the literature. The quantity of precipitate formation from reaction, or $m_{pr}$ can be calculated as follows:

a) Identify the chemical reactions that can occur based on the chemistry of mixing fluids as well as potential chemicals from hardware assembly, cleaning, permeation, etc.

b) Determine if precipitates can form by comparing the reaction quotient (Q) and solubility product (precipitate will form if $Q>K_{sp}$)

c) Calculate the reaction rate based on known or derived kinetic data (based on temperature and concentrations). Plot the mass of precipitate generated vs. time. If no rate data is available, assume the system instantaneously reaches equilibrium.

d) Calculate equilibrium composition of the system based on temperature, initial reactant concentrations, and pH of the system. Calculate the quantity of precipitate formed at equilibrium ($pd_p$).

e) Determine the duration of operation of the system ($t_{op}$).

f) Use the plot generated in #3 to predict the total mass of precipitate generated at any given time during operation or during the system operating lifetime. If the plot cannot be generated, use the equilibrium value calculated in #4 as the total precipitate generated in the system.

g) Determining particle size distribution of precipitate is particularly challenging. Predictive models have been generated but requires highly accurate kinetic data [ref. 49]. In the absence of high quality kinetic data, calculations should conservatively assume all particles in the smallest bin range of interest.

### Environmentally Induced Precipitation

Changes in system temperature, pH, the concentration of solutes, and quantity of solvents will affect the quantity of precipitate formed in a given system. Here we assume that a system is initially at equilibrium and calculate $m_{pe}$, the change in mass of precipitate due to environmental changes.

Temperature changes can result in increased precipitate formation ($+m_{pe}$) or decreased precipitate formation ($-m_{pe}$), depending on whether the reaction is endothermic or exothermic. Changes in pH either add or remove protons from solution, which can affect equilibrium and result in increased or decreased precipitate formation. Finally, evaporation of solvents, side reactions, absorption or desorption of molecules, etc. will change the concentration of the solutions and thereby affect precipitate formation. The quantitative impact of each of these can be calculated using the solubility product and is described in many basic chemistry textbooks, including some openly available [ref. 50].

## 3. Packed Bed System Degradation

For systems with packed beds, fines can be mechanically generated from the bed material due to particle-interactions caused by fluid flow or abrasion with containment surfaces or hydrothermal instability, and have been shown to cause harm to downstream valves and pumps [ref. 51]. Examples of particle generation from packed bed system degradation and design considerations to minimize particle generation are included in section 9.1.4. Methods for preventing, quantifying, and characterizing particle generation from degrading packed beds is a complex process dependent heavily on bed geometry, packing density, packing material properties, thermal cycling, and localized fluid dynamics [ref. 52]. An empirical approach to quantify and characterize particle generation from packed beds is provided below.

### Preventing Particulate Generation and Migration in Packed Beds

Packed beds composed of pelleted materials such as zeolites and catalysts, are inherently susceptible to particulate generation as the raw powdered materials are liberated from binders. Several best practices should serve to minimize the quantity of particles generated from the system:

a) Minimize void volumes in packed beds by implementing “snow storm” packing approaches when possible and through internal geometry design [ref. 53]

b) Size beds and system flow rates to prevent gas velocities known to induce material attrition [ref. 54]

c) Screen candidate packing materials using appropriate hydrothermal stability testing [refs. 55-57]

d) Design packed bed to accommodate changing bed size to maintain constant and evenly distributed compression of the bed [refs. 54, 58]

### Packed Bed Particulate Generation Rate Determination by Test

Although full scale systems provide the most accurate particle generation rate data, sub-scale testing of packed beds may be used to estimate the particulate generation rate so long as the bed aspect ratio, internal geometries, flow media, flow velocities, operational parameters (temperature, pressure, cyclic operation, etc.) are maintained.

Testing of the bed should be conducted in fully operational mode and mass of particulates generated ($pd_d$) measured as a function of time. Depending on the specific mechanisms of the fine generation for a given design, the rate of particulates may change over time. Duration of testing should be consistent with intended duration of operation. Characterization of the particles should be conducted at each time interval.

a) Plot the number of packed bed particulates generated (pdd) vs time for each bin size (n): (pdd-1, pdd-2, … pdd-n).
b) Curve fit the data to get an equation for particles (of a given size) as a function of time
c) Determine the duration of operation of the system (top)
d) Use the equation to calculate total quantity of particles generated over operational lifetime per bin size

In the absence of characterization data, particles may be assumed to be < 20µm [ref. 59]. Additionally, off-nominal thermal and pressure conditions should be tested to evaluate the worst-case particulate generation rates.

**<u>Packed Bed Particulate Generation Rate Prediction by Analysis</u>:**

Based on attrition testing of materials.

# Appendix I. Filter Requirements

Note: In the table below “I” refers to inspection, “A” refers to analysis, and “T” refers to test.

| Filter Requirements | | Verification | |
|---|---|---|---|
| | | **Acceptance** | **Qualification** |
| 3 | Component Requirements | | |
| 3.1 | Item Description | | |
| 3.2 | Performance Requirements | | |
| 3.2.1 | Operating Fluid | I | I |
| 3.2.2 | Pressure | | |
| 3.2.2.1 | Operating Pressure Range | —— | —— |
| 3.2.2.2 | Maximum Expected Operating Pressure (MEOP) | —— | —— |
| 3.2.2.3 | Maximum Design Pressure (MDP) | —— | —— |
| 3.2.2.4 | Proof Pressure | I,T | A,T |
| 3.2.2.5 | Burst Pressure | I | A,T |
| 3.2.2.6 | Element Forward Direction Collapse Pressure | I | A,T |
| 3.2.3 | Leakage | | |
| 3.2.3.1 | External Leakage | T | T |
| 3.2.4 | Flow & Pressure Drop | | |
| 3.2.4.1 | Flow Rate | —— | —— |
| 3.2.4.2 | Clean State Pressure Drop | I,T | A,T |
| 3.2.4.3 | Dirty State Pressure Drop | I | A,T |
| 3.2.4.4 | Reverse Flow Rate* | I | A,T |
| 3.2.4.5 | Reverse Flow Pressure Drop* | I | A,T |
| 3.2.4.6 | Reverse Flow Collapse Pressure* | I | A,T |
| 3.2.4.7 | Holding Capacity | —— | —— |
| 3.2.4.8 | Absolute Micron Rating | I,T | I |
| 3.2.4.9 | Nominal Micron Rating* | I,T | I |
| 3.2.5 | Physical Characteristics | | |
| 3.2.5.1 | Envelope Dimensions | I | I |
| 3.2.5.2 | Mass | I | I |
| 3.2.5.3 | Flow Direction Indicator | I | I |
| 3.2.5.4 | Filter Type | I | I |
| 3.2.6 | Life | | |
| 3.2.6.1 | Shelf Life | I | A |
| 3.2.6.2 | Service Life | I | A |
| 3.2.6.3 | Pressure Cycle Life | | |
| 3.2.6.3.1 | Operating Pressure Cycles | I | A,T |
| 3.2.6.3.2 | Proof Pressure Cycles | I | A,T |
| 3.3 | Component Interfaces | | |
| 3.3.1 | Fluid Interfaces | | |

| Filter Requirements | | Verification | |
|---|---|---|---|
| 3.3.1.1 | Inlet and Outlet Interface | I | I |
| 3.3.1.2 | Tube Stub Material and Construction | I | I |
| 3.3.2 | Mounting | I | I |
| 3.3.3 | Orientation | I | A,I |
| 3.3.4 | Line Loads | I | A |
| 3.4 | Environments | ▨ | ▨ |
| 3.4.1 | Operating Temperature | I | A |
| 3.4.2 | Non-Operating Temperature | I | A |
| 3.4.3 | External Pressure | I | A |
| 3.4.4 | Humidity | I | A |
| 3.4.5 | Random Vibration | A,T | A,T |
| 3.4.6 | Shock | I | T |
| 3.4.7 | Inertial Loads | I | A |
| 3.5 | Design and Construction | ▨ | ▨ |
| 3.5.1 | Material and Construction Standards | I | A,I |
| 3.5.2 | Fluid Compatibility | I | A,I |
| 3.5.3 | Housing Materials | I | I |
| 3.5.4 | Soft Good Materials | I | I |
| 3.5.5 | Filter Element Materials | I | I |
| 3.5.6 | Structural Design and Test Factors of Safety | I | A |
| 3.5.7 | Pressure Component | I,T | A,T |
| 3.5.8 | Threaded Joints | I | A |
| 3.5.9 | Bi-Metallic Joints | I | I |
| 3.5.10 | Electrical Bonding | T | T |
| 3.5.11 | Fasteners | I | A,I |
| 3.5.12 | External Cleanliness | T | T |
| 3.5.13 | Internal Cleanliness | T | T |
| 3.5.14 | Interchangeability | I | I |
| 3.6 | Part Marking and Identification | I | I |
| 3.7 | Traceability | ▨ | ▨ |
| 3.7.1 | Serialization | I | I |
| 3.8 | Reliability | I | A |

* If applicable

▨ Verification not applicable

____ Typically specified with “will” statements in a filter specification, not “shall” statements. Thus, direct verification is not required.

**<u>Shall</u>:** Indicates a requirement; must be implemented and verified.

**<u>Will</u>:** Indicates a statement of fact; not verified.

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**14. ABSTRACT**

NASA has provided little guidance for determining and implementing appropriate filtration of spaceflight propulsion and pressurant systems. Additionally, industry standards typically used for building and verifying filter performance are antiquated and lack applicability to propulsion systems. The NASA Engineering and Safety Center (NESC) was requested to perform a gap analysis, identify risks, and develop a mitigation plan for spaceflight propulsion filtration. This report contains the outcome of the NESC analysis.

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