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Analysis and Derivation of Allocations for Fiber Contaminants in Liquid Bipropellant Systems

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LIST OF ACRONYMS AND SYMBOLS

ASRDI	Aerospace Safety Research and Data Institute
ASTM	American Society for Testing and Materials
ET	external tank
FOD	foreign object debris
GOX	gaseous oxygen
GRC	Glenn Research Center
GSE	ground support equipment
KSC	Kennedy Space Center
LH_2	liquid hydrogen
LOX	liquid oxygen
MSFC	Marshall Space Flight Center
NVR	nonvolatile residue
PAR	Problem Action Record
PVC	polyvinyl chloride
PWR	Pratt & Whitney Rocketdyne
SSME	space shuttle main engine
UV	ultraviolet

NOMENCLATURE

D	larger circle diameter
d	smaller circle diameter
L	length
x	number of circles to fit

TECHNICAL PUBLICATION

ANALYSIS AND DERIVATION OF ALLOCATIONS FOR FIBER CONTAMINANTS IN LIQUID BIPROPELLANT SYSTEMS

1. INTRODUCTION

MSFC-SPEC-164, *Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems*, has established quantitative limits for particulate and nonvolatile residue (NVR) contamination in liquid bipropellant systems manufactured or refurbished at or for NASA's George C. Marshall Space Flight Center (MSFC).[1] Originating in 1962, this specification has never included specific allocations or size limits for fiber contaminants as a distinct particle type. Fibers, however, are often more difficult to control than other types of particles during precision cleaning and assembly of large components. Fibers are readily transported in air currents and deposited on hardware. Fibers also can slip through screens in cleaning equipment, defeating the filtration systems intended to keep the cleaning agent free of particulate.

The presence of a fiber in a component cleanliness verification sample may result in a rejection, requiring the shop to reclean the part. This has been a recurring challenge at MSFC when processing large components for launch vehicles and their corresponding propulsion test systems, driving up processing costs. Some difficult to clean parts, such as liquid oxygen (LOX) system pressure regulators, frequently require multiple cleaning cycles to eliminate fibers.

At the request of the MSFC Engineering Test Valve and Components Lab, an analysis was performed to determine whether the internal contamination limits for liquid propulsion systems could be revised to provide an allocation for fibers beyond the established particulate limits.

2. BACKGROUND AND ANALYTICAL APPROACH

A particle is any minute quantity of matter, metallic or nonmetallic, with observable length, width, and thickness (see ref. 1, app. C—Definitions). Particulate contaminants within liquid bipropellant systems can have a number of deleterious effects on system performance and safety. These contaminants can plug or restrict flow through filters and orifices and can create leak paths or mechanical interference in pumps, valves, and regulators. In LOX systems, particles can, under certain conditions, cause impact ignition. Both particulate and film residue contaminants can be ignited in LOX systems by other mechanisms.

A fiber is defined as a particle having a length-to-width ratio (aspect ratio) of 10:1 or greater.[1] Most fiber contaminants, such as cotton clothing fibers, have a length-to-width ratio many times greater than this. Some cleaning specifications used within the aerospace industry also state that a fiber must have a length of 100 µm or greater,[2–4] must have a diameter of <40 µm,[5] or must be nonmetallic and flexible.[6] MSFC and many aerospace companies, however, have avoided requirements stating that certain particle contaminants must be nonmetallic or flexible as these characteristics are difficult to determine conclusively by simple visual or microscopic evaluation and cannot be determined by automated image analysis or light-scattering methods.

The baseline version of MSFC-SPEC-164, originally released in 1962, contained detailed instructions for cleaning the components of liquid bipropellant systems for both flight systems and ground support systems. This document specified one quantified limit for particulate contamination that was applied to all components. MSFC-SPEC-164 underwent a major rewrite in 1994, released as revision B. In revision B, three additional classes of particulate cleanliness were added, with the original particulate cleanliness requirement retained as class I and identified as the default cleanliness level to be used when no level is specified by drawing. MSFC-SPEC-164B contained an appendix, "Space Shuttle Cleanliness Requirements," which showed that class I was only applied to flight pneumatic systems in the external tank (ET).[7] The limits for NVR were established in the baseline release and have never been modified.* Written rationales for the baseline contamination limits in MSFC-SPEC-164 have not been located.

The first task when challenging an existing requirement is to understand, and if necessary, reconstruct, the rationale for that requirement. Once the rationale for a requirement is sufficiently understood, changes to the requirement can be analyzed using the same rationale to determine the impact of the change. A risk analysis must also be performed to determine whether the change could have other consequences that would render it unacceptable.

---

*In MSFC-SPEC-164, revision B, to eliminate hybrid English/metric units, the contamination limits were changed from maximum number (particulate) or mg (NVR) per ft^2 to per 0.1 m^2. This change is only slightly more conservative and not considered significant. A note in both revisions B and C states that "for the purpose of this specification, 0.1 square meter = 1 square foot."

The steps used to analyze the system tolerance for fibers were as follows:

(1) Understand the technical rationale for the current particulate limits via a search for published historical rationale and by deriving them from historical system design and performance criteria.

(2) Based on this rationale, identify and analyze the potential consequences of allowing fibers larger than the current particulate limits.

(3) Identify other potential risks, apart from those directly related to the derived technical rationale, that must be considered and determine whether those risks are of significance.

(4) Compare the fiber size and quantity limits identified for each risk scenario to determine the risk drivers and associated maximum fiber size and quantity to establish allocations.

(5) Determine whether there is a precedent in published data for other liquid hydrogen (LH_2) and LOX systems for the size and quantity allocations derived in step (4).

3. LIMITATIONS OF THIS ANALYSIS

This analysis addresses particulate contaminants in LOX/LH_2 bipropellant systems and associated helium and nitrogen pressurization systems. Assumptions are based on published NASA and industry data for LOX and LH_2 propellant systems from the Saturn program to the present. The results of this analysis may not be applicable to high-pressure gaseous oxygen (GOX) systems such as those used for life support systems, fuel cells, extravehicular activity suits, and orbital maneuvering units.

The results of this analysis will apply to the corresponding helium and nitrogen pneumatic and ullage systems that interface with the LOX and LH_2 systems, as a minimum. Some valves and regulators for these systems require cleaner particulate levels. Particulate and fiber cleanliness requirements for the systems upstream of these components must be derived to prevent damage to the components or excessive restriction of the filters protecting them.

New engines and propulsion system designs for future launch vehicles may require different particle contamination limits and associated fiber contamination limits. The rationale and assumptions used to derive the contamination limits in MSFC-SPEC-164 must be reevaluated for application to a new propulsion system design.

4. PRECEDENT FOR FIBER ALLOCATIONS

A literature search was performed to determine whether there is current or historical precedent for fiber allocations in LOX/LH_2 propellant fluid systems. Several significant sources were identified where fiber limits were established for LOX/LH_2 propulsion systems as well as high-pressure GOX systems that exceeded the particle size limits for those systems.

The Compressed Gas Association standard CGA G-4.1-2009, *Cleaning Equipment for Oxygen Service,* clearly allows for the presence of lint fibers as long as there are no accumulations.[8] The section on visual ultraviolet (UV) inspection states that "some materials such as cotton lint that fluoresce are acceptable unless present in excessive amounts." This document further states that when quantified limits for particulate are specified, typical specifications limit particles to no more than 1,000 µm, with no more than 20 particles/ft^2 (0.1 m^2) between 500 and 1,000 µm, and isolated fibers of lint to no longer than 2,000 µm with no accumulation. The repeated use of the terms "cotton lint" and "lint fibers" implies that these fibers are assumed to be nonmetallic, as opposed to metal "filings" which are noted elsewhere in the document as another form of contamination.

Pratt & Whitney Rocketdyne (PWR) specification RA0110-004, *Cleaning and Handling Parts for Propellant, Pneumatic, and Hydraulic Service*, details cleaning practice for some of their rocket engines.[5] This document specifies allocations for fibers up to 6,000 µm in oxidizer, fuel, pneumatic, and hydraulic systems. A fiber is defined as solid matter having a diameter of <40 µm. The particle and fiber limits are the same for all systems. This specification, however, is one of PWR's older specifications, used on expendable engines, and does not reflect current practice on other engines (V.M. Douglas, Nonmetallic Materials Technology, PWR, Private Communication, August 31, 2011).

The NASA Glenn Research Center (GRC) Safety Manual GLM-QS-1700.1, chapter 5 on oxygen systems,[9] specifies contamination limits for GOX/LOX service in GRC test facility systems. The cleanliness limits include allocations for particles and fibers in defined size ranges, with allowed particles no larger than 300 µm in maximum dimension and fibers no larger than 1,875 µm in length and 25 µm in diameter per square foot of sampled area. This specification also establishes a limit for total solids and fibers of 25 mg/0.1 m^2. Pressure gauges and transducers certified oxygen-clean, while requiring the same fiber limits, are permitted to contain particles up to 500 µm. The Lewis Safety Manual (NASA Lewis Research Center is now GRC), dated November 1992,[10] is evidence that these particle and fiber limits have been in use since at least 1992.

A detailed survey, published as NASA SP-3072, was performed in 1972 by the Aerospace Safety Research and Data Institute, NASA Lewis Research Center, to document current practice in the aerospace industry for cleaning oxygen systems.[11] Twenty oxygen system cleanliness specifications were referenced in the survey report, including specifications for spacecraft and aircraft breathing oxygen systems, manned launch vehicle and missile propulsion systems, and commercial systems. Fourteen of these specifications contained allocations for fiber contaminants that exceeded the maximum dimension of the corresponding particle limit. The fiber length limits exceed the particle size limits by a factor of 2 to a factor of 10. The maximum allowed fiber length was 6,000 μ; fiber length limits around 2,000 μm were more common. Apparently, the contamination limits for oxygen systems now in use at GRC were derived from this survey.

In addition to the above sources documenting common use of fiber allocations in the aerospace industry since the 1960's, SD 70-557-5, a sustaining engineering report from the Saturn S-II program,[12] recommended specific fiber allocations for future S-II production. This document, starting from MSFC-SPEC-164A (now MSFC-SPEC-164C, class I) as the basis, recommended that the allocation for one particle 700 to 2,500 μm per square foot be restricted to nonmetallic fibers only. The recommendations from this report were not captured in subsequent revisions of MSFC-SPEC-164. No more S-II stages were built.

5. DERIVATION OF RATIONALE FOR THE CURRENT PARTICULATE LIMITS

The analyses here are based on the main propulsion system designs for the space shuttle and the Ares I launch vehicles. These systems were required to be cleaned in accordance with MSFC-SPEC-164, revisions B and C, respectively. Both designs used LH_2 as the fuel and LOX as the oxidizer. Both systems also used PWR engines that required propellants compliant with a common specification, RA0615-072, *Use Limits for SSME Propellants and Propellant Pressurizing Agents*.[13] The upper stage engine for the Ares I vehicle, the J-2X, was a derivative of the J-2 engine used on the second and third stages of the Saturn V rocket, which is assumed to have also required the same propellant contamination limits. The PWR propellant specification for the J2-X dates back to at least 1972. Therefore, it is assumed that the basis for the original particulate contamination limits in MSFC-SPEC-164, released early in the Apollo program, is the same as for the Ares I.

The particulate levels in MSFC-SPEC-164C are shown in table 1. Particle size is measured by the longest dimension. Class I, which permits one particle up to 2,500 µm but severely restricts the presence of particles down to 175 µm, dates back to the origin of MSFC-SPEC-164, April 16, 1962. The "no silting" restriction was added in revision B. All fuel, oxidizer, and associated pneumatic systems were cleaned to this level with the exception of nonmetallic miscellaneous components. Nonmetallic components that could be degraded by the trichloroethylene solvent originally specified for quantitative verification were permitted to be verified by visual inspection alone.

Table 1. Classification of particulate cleanliness in MSFC-SPEC-164C.

Class	Particle Size (µm)	Maximum Number (per 0.1 m^2)
I	>2,500 700 < x ≤2,500 175 < x ≤700 No silting	0 1 5
II	>1,000 700 < x ≤1,000 175 < x ≤700 No silting	0 40 150
III	>800 No silting	0
III X	>800 175 < x ≤800 No silting	0 5
IV	>400 No silting	0
IV X	>400 175 < x ≤400 No silting	0 5
V	Visually clean/no silting	

The PWR propellant specification imposes size limits of 400 and 800 μm, respectively, for allowable particulate in LH_2 and LOX. These are reported by PWR to have been derived from the smallest system orifice diameters using the conservative three-ball approach.[14] This approach uses the three-ball equation to establish the maximum particle diameter that will permit three balls (contaminant particles) to pass through the smallest system orifice simultaneously. Limiting all particulate contamination to below this size will minimize the risk that particulate will lodge in a critical orifice, blocking or restricting propellant flow. Such blockage or restriction could inhibit engine performance during launch and result in a loss of mission.

The particulate cleanliness limits established for the space shuttle main engine (SSME), also known as the RS-25, in the 1970's were also based on critical orifice sizes. However, the three-ball equation was not used and the particle limits were less conservative. In the SSME Contamination Control Plan,[15] for orifice sizes of 450 μm (a slot) in the LH_2 system and 900 μm in the LOX system, particulate size limits of 400 and 800, respectively, were applied.

The formula for calculating the diameters of a specified number of circles of equal size that will fit side by side within a larger circle is:

$$d = D * \sin(\pi / x) / \left(1 + \sin(\pi / x)\right) \ , \tag{1}$$

where d = the smaller circle diameter, D = the larger circle diameter, and x = the number of circles to fit ring-like (x = 2,3,...).

For the three-ball calculation, the smaller circle diameter (d) corresponds to the diameter of the maximum allowable particle size, the large circle diameter (D) is the orifice size, and the number of circles to fit (x) is 3. Therefore:

$$\begin{aligned} d &= D * \sin(\pi / 3) / \left(1 + \sin(\pi / 3)\right) = D * \sin(1.0472) / (1 + \sin(1.0472) \\ &= D * (0.86603) / (1.86603) = D * (0.4641) \ . \end{aligned} \tag{2}$$

Seven/sixteenths of the orifice diameter (D*(0.4375)) may be used as a simple, conservative approximation.

Calculating with the three-ball equation, particle size limits of 400 μm for the LH_2 system and 800 μm for the LOX system indicate that the smallest downstream orifices to be protected (in the engine) are ≥862 μm (0.034 in) and 1,724 μm (0.068 in), respectively. PWR, however, has reported that establishing the particulate limits based on the three-ball calculation was a "goal" and that the downstream orifices in the J2-X engine are actually smaller than would be indicated by this calculation (M.A. Sylvia, Materials & Processes, Contamination Control, PWR, Private Communication, September 8, 2011). Actual critical orifice sizes in the J2-X engine were not available for this analysis. To be conservative, where critical orifice size was a decisive factor for this analysis, the published orifice sizes for the SSME were used.

MSFC-SPEC-164, revision B established classes III and IV for oxygen system components and hydrogen system components, respectively, that feed the engine downstream of the propellant tank filter screens.[7] Given the difficulty of meeting, these particulate limits on the entire surface area of the main propellant tanks, a less stringent limit, class II, was established for the tanks. The orifice sizes for the tank feed filters are the same as the maximum allowed particle size for the propellants; i.e., 400 and 800 μm. Propulsion test stands are also required to meet these cleanliness limits to prevent contamination of engines and integrated stages during green runs and development tests.

The smallest particle size with limits in MSFC-SPEC-164, 175 μm, can be derived as the maximum allowable particle size for a 400-μm orifice using the simple approximation (7/16) of the three-ball equation. The "no silting" requirement, added in revision B, was likely established to assure accurate particle counts and to avoid the presence of excessive quantities of finer contaminants that could agglomerate and act as larger particles or as combustible matter. At least one industry study indicated that, under some circumstances, an excessive quantity of particles smaller than 40 μm could cause an ignition due to particle impact.[16] Silting may also be a warning sign that hardware has corroded or the cleaning system has become contaminated. Silting is defined as an accumulation of minute particles in the size range not normally counted but of sufficient quantity to interfere with sample analysis.[1]

The original particle limits, now shown as class I, permitted five particles 175 to 700 μm per square foot and one particle per square foot up to 2,500 μm. These limits applied to all components throughout the system. The 700 and 2,500 μm limits do not correlate, directly or via the three-ball equation, to any known system orifice size. It has been reported that these larger particle allocations were derived from actual "field tests" at the Kennedy Space Center (KSC) complexes and represent the maximum cleanliness results obtainable in the field during the 1960–1964 time period (ref. 11, p. 4).

It should be noted that current designs for ambient and cryogenic helium regulator sets and other pneumatic system components integral to bipropellant propulsion systems require protection from particulate smaller than 175 μm. These components are cleaned to levels more stringent than those specified in MSFC-SPEC-164, table I, and are generally protected by in-line filters on the order of 25 to 100 μm. Systems upstream of the components and filters must be cleaned accordingly to prevent plugging or restriction of these in-line filters during system operation. Cleaning of these components is specified to meet a more stringent cleanliness level, usually per IEST-STD-CC1246, *Product Cleanliness Levels and Contamination Control Program*,[17] or a modification thereof.[18] Cleanliness levels not specified in MSFC-SPEC-164, table I, are not addressed in this analysis. However, the same rationale for establishing limits for fibers versus particulate based on prevention of filter plugging or restriction may be applicable to these systems as well.

6. FIBER LIMITS BASED ON CRITICAL ORIFICE PLUGGING

Analysis of the tolerance of a system to fiber contamination based on orifice plugging must consider contaminant locations upstream and downstream of the propellant tank feed filters. Fiber contaminants downstream of the tank feed filters must not present a greater risk of plugging the critical engine orifices than the baseline 400- or 800-μm particle size limits. Fiber contaminants upstream of the tank filters, which are 400- or 800-μm absolute rated screens, must not present a greater risk of restricting flow through these screens. Fibers from the tanks that pass through the tank filter screens lengthwise during operation also must not present a greater risk to the critical engine orifices.

Using the 10:1 aspect ratio for fiber width to length as worst case, several scenarios are considered for the potential to plug or restrict 400- or 800-μm orifices. These orifice sizes reflect the pore sizes of the tank filter screens. The critical engine orifices downstream are significantly larger, further reducing the probability that fibers, permitted based on the tank filter pore size, will restrict flow.

6.1 Scenario 1: Fibers Pass Through the Orifice Lengthwise

Assuming that all fibers entrained in flowing fluid will orient lengthwise, passing any orifice larger than the width of the fiber, the maximum allowable particle length is theoretically unlimited. The allowable particle width would be the same as the allowed particle diameter. However, fibers pose additional risks for orifice plugging beyond particulate. The increased length of a fiber increases the time required for that fiber to pass through an orifice. This greatly increases the probability of orifice plugging due to multiple fibers or particles encountering an orifice simultaneously. Assuming that the ratio of the downstream critical orifice to the upstream filter screen adheres to the three-ball calculation, limiting the width of all fibers in the system, downstream or upstream of the tank filter screens, to that based on the three-ball calculation for the screen pore size rather than the downstream orifice size will yield an allowed fiber width of (0.4641×0.4641) or 21.5% of the downstream orifice size. The downstream orifice will pass as many as 16 fibers of this width without plugging.**

Allowing fibers in each system with a maximum length of 10 times the approximated (7/16) three ball calculation for the tank filter screen pore size, 1,750 μm (LH_2) and 3,500 μm (LOX), and quantities limited by the “no silting” requirement, would appear to be conservative. It should be noted that such fibers at the maximum aspect ratio of 10:1 would be clearly visible to the unaided eye and would not pass the visual inspection requirement. Fibers of these lengths with widths <50 μm are more typical of environmental fibers such as clothing fibers. These would pose an insignificant risk of critical orifice plugging. Table 2 shows the number of fibers that could theoretically pass through an orifice simultaneously, based on best known packing calculations of equal circles within a larger circle.

**Calculation of the packing of equal circles beyond seven within a larger circle becomes complicated, as there is extra space. Several internet sources on circle packing point to this article for packing of 16 equal circles into a larger circle.[19]

Table 2. Number of fibers that can pass lengthwise through an orifice simultaneously.[20]

Fiber Diameter (μm)	Orifice Size 400 μm	800 μm	862 μm*	1,724 μm*
100	11	50	59	249
70	24	106	124	519
50	50	213	249	1,032

*Calculated downstream orifice sizes assuming that the filter screen pore size was selected based on the three-ball calculation from the downstream orifice size.

6.2 Scenario 2: Fibers Passing Through the Orifice are Bent Double or Broken in Half

Scenario 1 assumes that each fiber will align with the fluid flow and pass through the orifice end-on. An accumulation of fibers could be deposited on the surface of a filter, either during fill and drain of a system prior to launch or by settling during shipment while the stage is filled with purge air rather than fluid. If the fibers are deposited crosswise on the filter screen prior to initiation of flow, they may either remain in place, be swept through lengthwise, or pass through the orifice doubled should they either fold in two or break under the force of the flow, thus acting as two fibers. Assuming that these fibers pass through doubled, the number of fibers that could theoretically pass the orifice is one-half the numbers shown in table 2, to the next lower even number of fibers. The result is shown in table 3.

Table 3. Number of doubled fibers that can pass lengthwise through an orifice simultaneously.

Fiber Diameter (μm)	Orifice Size 400 μm	800 μm	862 μm	1,724 μm
100	5	25	29	124
70	12	53	62	259
50	25	106	124	516

Given that fibers are much longer than particles and therefore take longer to pass through an orifice, the opportunity for fibers to pass through an orifice simultaneously is much greater than particles. There is, therefore, some question whether 100-μm-diameter fibers should be permitted in a system with a 400-μm critical orifice, where six folded or broken fibers could block an orifice. Narrowing the allowable fiber diameter to 70 μm would add conservatism and still accommodate the most common and troublesome environmental fibers. However, 400 μm is the orifice diameter of the filter used to protect a larger downstream critical orifice. Even if the critical orifice is only slightly larger than the filter pore size, the number of fibers that may pass lengthwise, even doubled over, increases substantially. For example, a 450-μm-diameter critical orifice will simultaneously pass up to seven doubled 100-μm-wide fibers and up to 32 doubled 50-μm-wide fibers.

This analysis assumes either broken or perfectly folded fibers with a zero bend radius. The idealized case of fibers folded with a zero bend radius is unlikely. Restricting the fibers to <50 μm diameter yields a generous margin for imperfectly folded fibers. Fibers that are bent but not tightly folded are addressed in scenario 3.

It should be noted that the filter screens used in liquid bipropellant system tanks are constructed of woven wire mesh, with pore size defined by an absolute glass bead rating. The orifices are actually square, with ≈22% more flow area than a round orifice of the same width. Whereas a circular orifice will pass three particles <0.4641 times its diameter, a square of the same width will pass three particles <0.5087 times its width. The number of fibers of smaller diameter that can pass lengthwise simultaneously through a square orifice also rises significantly. The worst case scenario shown in table 3, where up to five doubled 100-μm fibers will pass through a 400-μm round orifice, compares to eight doubled 100-μm fibers that may pass through a 400-μm square orifice. This is illustrated in figure 1.

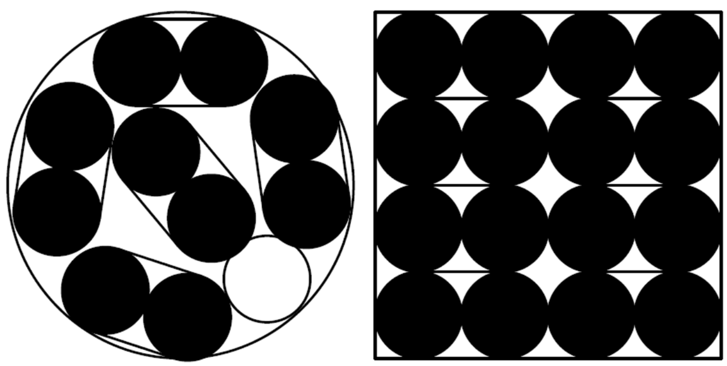

Figure 1. Packing of doubled fibers in a square versus a circle of the same width.

6.3 Scenario 3: Fibers Passing Through the Orifice are Rigid and Bent or Twisted

It is assumed in scenarios 1 and 2 that all of the fibers are either straight or are sufficiently flexible to pass the orifice lengthwise without interference. Natural clothing fibers, however, are not typically straight. Cotton, linen, and wool are twisted when observed under magnification. If these fibers also become inflexible at cryogenic temperatures, they will not pass an orifice in a parallel orientation.

Fibers shorter than the width of the critical orifice will pass unhindered regardless of their shape. Long, twisted, rigid fibers will most likely be captured by filters as the probability of the fibers lining up in an orderly fashion with the flow is significantly reduced. Should these rigid, twisted fibers be present downstream, where they could lodge at the entrance to a critical orifice, they will still present a significantly lower risk of restricting flow than particles of the maximum allowed size. When the width of fibers is restricted to <50–100 μm, even very long fibers pose little obstacle to fluid flow or to the passage of particles restricted to 7/16 of the orifice size (illustrated in fig. 2).

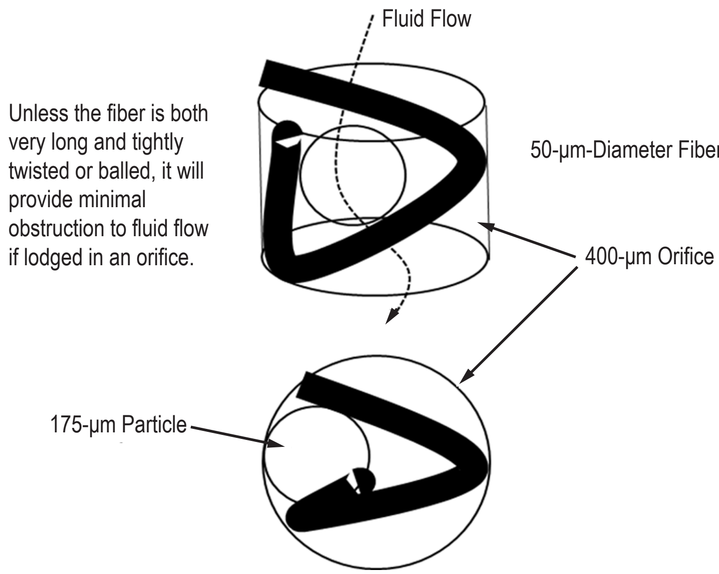

Figure 2. Twisted fiber lodged in an orifice.

Fibers would need to be tightly bent and 2.5 or more times the diameter of the critical orifice in length to begin to create an obstruction sufficient to collect particles within the orifice.

6.4 Scenario 4: Fibers and Particles Combine to Restrict the Orifice

If rigid fibers, whether straight or twisted, land across the critical orifice rather than passing through, and are not simply swept aside by the fluid flow, then the flow restriction caused by either multiple fibers or combinations of fibers and particles must be considered. Assuming that not more than three particles of any type will encounter an orifice simultaneously, the worst case scenario involving a fiber is for two particles and one fiber to encounter the orifice simultaneously, with the orifice fiber landing crosswise. Using the three-ball calculation to establish the particle size limit, fiber widths of up to 0.0718 times the diameter of the circular orifice will not cause an obstruction and can be permitted without limit:

$$D = \left(D*(0.4641) + D*(0.4641)\right) + D*(x) \geq x = 0.0718 \quad . \tag{3}$$

Using the approximation of 7/16 times the orifice diameter to set the maximum particle size, the maximum fiber width becomes 1/8 times the orifice diameter. Thus, for a 400-µm orifice and a maximum particle size of 175 µm, fibers up to 50 µm in diameter can be allowed without limit (illustrated in fig. 3).

The relative level of restriction of the orifice can be calculated for each combination of up to three particles or fibers using the two-dimensional shadow of each contaminant as the worst case. The area of the obscuring particles versus the area of the orifice yields an obstruction ratio. Figures 4–6 show the various permutations of 50-µm-diameter fibers and 186-µm-diameter particles (the actual three-ball limit) obscuring 400-µm round and square orifices and their resulting obscuration ratios.

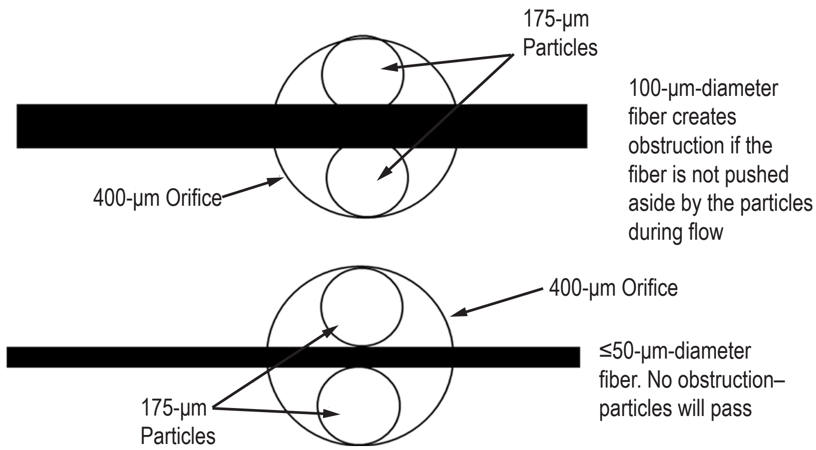

Figure 3. Orifice obstruction by two particles and one fiber.

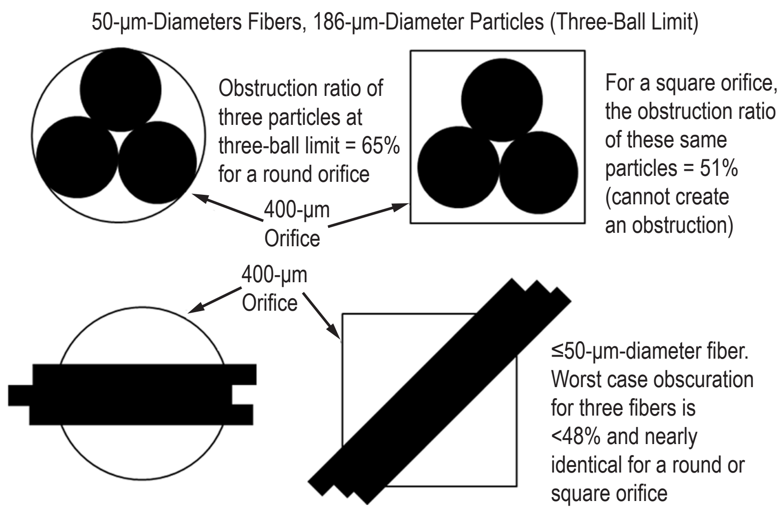

Figure 4. Obstruction ratios of three round particles versus three parallel fibers.

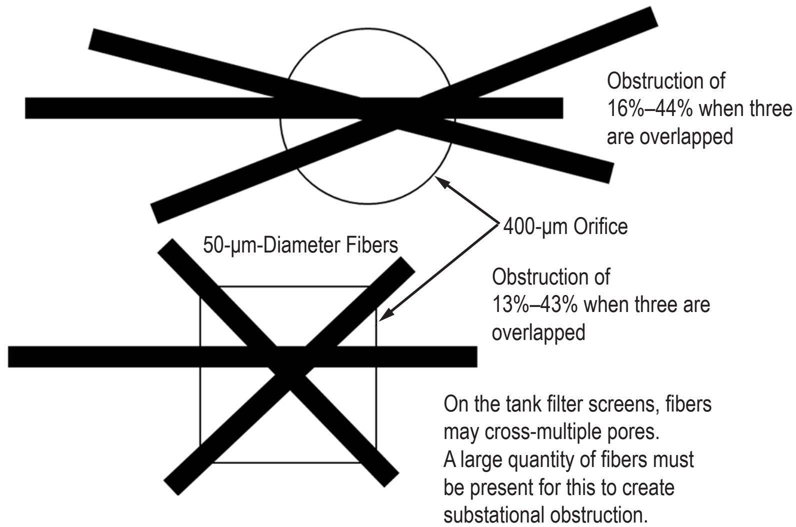

Figure 5. Obstruction ratios resulting from overlapped fibers.

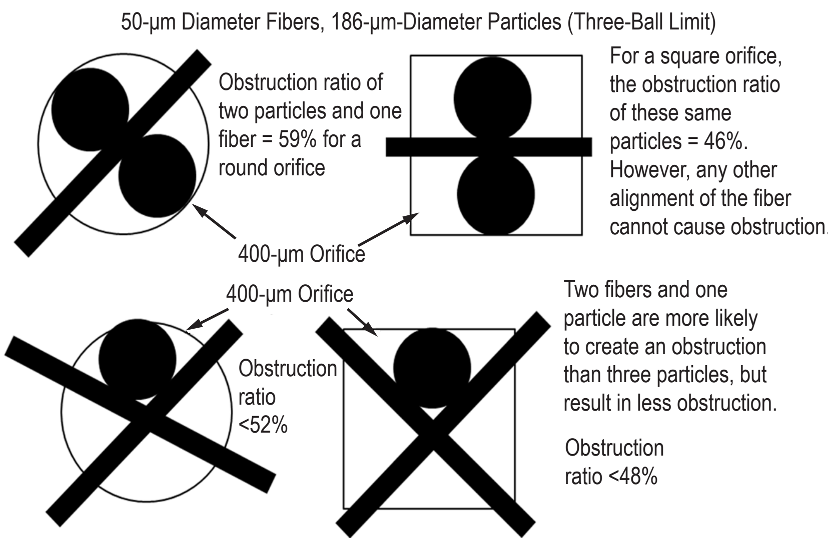

Figure 6. Alternate contaminant orientations and their maximum obstruction ratios.

It can be seen in figure 6 that one 50-µm fiber and two 186-µm particles can cause obstruction of a square 400-µm orifice if the fiber lands just right. Likewise, two fibers and one particle of these sizes, oriented just right, can cause obstruction of a circular 400-µm orifice. The overlap is slight and, when multiplied with the low probability that the three contaminants will encounter the orifice simultaneously, the required orientation is highly improbable. Furthermore, the resulting obscuration ratio is lower in each case than obstruction by three particles.

It is assumed for the calculations shown in figures 4–6 that the fibers are straight. Fibers that are not straight will not line up side by side as shown in figure 4 to obstruct flow. Twisted fibers would be unlikely to cause more flow restriction than shown in figures 5 or 6.

6.5 Conclusions Based on Critical Orifice Plugging or Restriction

Based on the above analyses, an unlimited number of fibers of a length less than or equal to the diameter of the critical downstream orifice size can be tolerated without reservation. Longer fibers, when limited to a maximum width of 50 µm or less should be acceptable in the LH_2 system without risk. Given that the downstream critical orifices are larger than the 400-µm orifice used in these calculations, and that some restriction of the filter screens is acceptable, fibers up to 70 µm or even 100 µm in diameter should be acceptable. The LOX system, with orifices assumed to be 900 µm or wider, should be able to tolerate fibers as wide as 100 µm without obstruction. If the smallest critical orifice is a slot rather than circular, as was the case in the SSME LH_2 system, then the probability of plugging by these larger fibers is even less likely.

These calculations do not point to a hard upper limit for length of fibers or quantity. To minimize the probability that rigid twisted fibers will create an obstruction within an orifice, the maximum length of fibers should be limited to <2.5 times the diameter of the downstream critical orifice. Based on the SSME orifice sizes, conservative maximum length for fibers should be 1,000 µm in the LH_2 system and 2,000 µm in the LOX system.

Without detailed knowledge of fluid system surface areas, filter designs, and filter locations internal to the engine(s), a maximum allocation for quantity of fibers cannot be determined. However, an allocation of two fibers per sample smaller than 50 µm diameter × 1,000 µm long provides less surface area restriction than one particle 400 µm in maximum dimension. Two fibers per sample smaller than 100 µm diameter × 2,000 µm long provides less surface area restriction than one particle 800 µm in maximum dimension. This would seem to be a conservative allocation.

In the propellant tanks, long, twisted fibers capable of being lodged in a critical orifice will be prevented from reaching the orifice by the tank filter screens. Straight fibers, however, when aligned with the direction of fluid flow, will bypass the tank filter. Fibers present in the tanks must also be restricted to the maximum diameter required for the downstream system.

None of the above scenarios require that the fibers be nonmetallic. Restrictions on fiber composition may be based on other potential failure mechanisms for a system.

7. OTHER POTENTIAL FAILURE MECHANISMS DUE TO FIBERS

Other potential failure mechanisms from fiber contamination that must be considered include excessive restriction of system filters, valve seal leakage, and potential ignition of contaminants in LOX systems. As a baseline for these analyses, it is assumed that the allocations for size and quantity of particulate established for the space shuttle ET, defined by MSFC-SPEC-164, are acceptable for future liquid bipropellant launch systems with the same or larger downstream orifice sizes.

7.1 Filter Face Obscuration Leading to Flow Restriction

Scenarios 1–3 above assume that particles will align with the flow and encounter the orifice lengthwise, generally passing though. Scenario 4 considered the potential for fibers or a combination of fibers and particles to block a critical orifice. If, as noted in scenario 4, the fibers become rigid at cryogenic temperatures and do not align with the flow, then the potential also exists for a quantity of fibers to accumulate on the filter face upstream of a critical orifice and restrict flow. To manage this risk, an allocation must be established for fibers to limit the potential restriction to an acceptable level.

To fully analyze the potential for fibers to obscure a filter face to an unacceptable degree, the area of the filter face and the allowable restriction must be known. The total internal surface area upstream of the filter also determines the total fiber load that is potentially available to travel downstream to the filter. This can be approximated using the shuttle ET system as a worst case. The system performance details that determine allowable restriction were not available for this analysis. However, it is possible to evaluate the relative restriction potential of fibers versus particles accumulated on a filter surface. Assuming that the current allocations for particles upstream of system filters are acceptable, equivalent allocations for fibers can be calculated.

Using the two-dimensional area, or "shadow" of the particle as the measure of restriction potential for particles larger than the orifice size of the filter, relative restriction of particles versus fibers can be calculated. This is a simplification since particles and fibers are three-dimensional and rarely appear as disks or ribbons. This simplification, however, is conservative because fluids will more easily flow around round, cylindrical, or irregular particles.

For the lowest fiber aspect ratio (by definition) of 10:1, the fiber length that equates to the shadow area of a round particle is calculated as follows:

$$L \times W = L \times L / 10 = L^2 / 10 \ldots L^2 / 10 = \pi r^2$$
$$\downarrow$$
$$L = \sqrt{\left(\pi (D / 2)^2 \times 10\right)} \ , \qquad (4)$$

where L = the length of a fiber with aspect ratio 10:1 and D = the diameter of the particle.

A 10:1 fiber with a length 2.8 times the diameter of the particle yields equivalent obscuration (shadow area). This relationship is shown in figure 7.

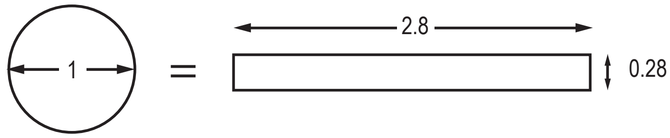

Figure 7. A fiber of aspect ratio 10:1 and a particle of equivalent obscured area.

Based on equivalent filter face obscuration, the lengths and quantities of fibers permitted for each class of particulate cleanliness in MSFC-SPEC-164C are shown in table 4. It should be noted that the larger fibers, if present at the 10:1 aspect ratio, would be clearly visible as debris.

Table 4. MSFC-SPEC-164C classes with equivalent fiber lengths based on obscuration.

Class	Particle Size (μm)	Maximum No. (per 0.1 m^2)	Length of Equivalent Fiber at 10:1 Aspect Ratio (μm)	Length of Equivalent Fiber With 100 μm Diameter (μm)	Length of Equivalent Fiber With 50 μm Diameter (μm)
I	>2,500 700 < x ≤ 2,500 175 < x ≤ 700 No silting	0 1 5	>7,000 1,960 < x ≤ 7,000 490 < x ≤ 1,960	>49,063 3,847 < x ≤ 49,062 240* < x ≤ 3,847	>98,125 7,693 < x ≤ 98,125 481* < x ≤ 7,693
II	>1,000 700 < x ≤ 1,000 175 < x ≤ 700 No silting	0 40 150	>2,800 1,960 < x ≤ 2,800 490 < x ≤ 1,960	>7,850 3,847 < x ≤ 7,850 240*< x ≤ 3,847	>15,700 7,693< x ≤ 15,700 481*< x ≤ 7,693
III	>800 No silting	0	>2,240	>5,024	>10,048
III X	>800 175 < x ≤ 800 No silting	0 5	>2,240 490 < x ≤ 2,240	>5,024 240* < x ≤ 5,024	>10,048 481* < x ≤ 10,048
IV	>400 No silting	0	>1,120	>1,256	>2,512
IV X	>400 175 < x ≤ 400 No silting	0 5	>1,120 490 < x ≤ 1,120	>1,256 240* < x ≤ 1,256	>2,512 481* < x ≤ 2,512
V	Visually clean/no silting				

* Does not meet the minimum 10:1 aspect ratio for a fiber.

If fibers are limited to a diameter of 100 or 50 μm due to concerns over plugging of individual orifices downstream, then the fiber length that will create an equivalent level of obstruction versus a round particle becomes much longer for the larger particle sizes. This is shown in the two right columns of table 4. These thin fibers become absurdly long when equated to particles larger than 800 μm, with lengths better measured in centimeters than micrometers.

As shown in table 4, the allocations for two fibers per square foot, at no larger than 50 µm diameter by 1,000 µm long in the fuel system and no larger than 100 µm diameter by 2,000 µm long in the oxygen system, yield less obscuration than one maximum size particle for those systems.

Allocations for fibers in the propellant tanks must consider both restriction of the tank filters and restriction of downstream filters within the engine by straight fibers that bypass the tank filter. While it could be assumed that 50- or 100-µm-diameter fibers that are able to bypass the tank filter will also bypass engine filters and be ingested, a conservative approach would assume that at least some of these fibers will land on the engine filters. In addition to the level II particle limits established for the space shuttle main propulsion tanks, one fiber per square foot may be permitted, up to 50 µm in diameter and 1,000–2,500 µm long in the fuel tank and up to 100 µm in diameter and 1,000–5,000 µm long in the LOX tank.

7.2 Valve Seal Leakage

A single particle of contamination, if sufficiently large and positioned on a sealing surface, can prevent a valve from fully closing, creating a leak path for propellants or pressurants. Abrasive particles in excessive quantities can also, over time, erode seats and seals, resulting in leakage. All propulsion system valves and seals have allocations for allowable leakage.

It is difficult to calculate or predict the minimum size particle that will cause a valve to leak. Valve seals are designed to deform around minor surface variations and small contaminants to assure a good seal. This is true even for metal sealing surfaces in oxygen systems. These surfaces are composed of relatively soft metal alloys or metals coated with oxygen-compatible, nonmetal coatings that are slightly compliant.

The tolerance of valve seat coatings to leakage from hard particle contamination has been studied. A study performed by McDonnell Douglas Astronautics Co. in 1975 for Lewis Research Center tested the contamination tolerance of various nonmetallic coatings on valve seats.[21] This study concluded that particles will be embedded in coatings of relatively hard plastic materials such as Xylan® 1010, Kynar® 202, and Teflon® S, without resulting in leakage. While some particle deformation generally occurs during embedment, a coating thickness of 20%–30% more than the largest anticipated particle diameter was recommended. Particles up to 420 µm were tested to verify leakage resistance. Assuming that seals will crush very thin, twisted fibers down to their diameter and deform around them, even metallic fibers limited to 50–100 µm in diameter should be of minimal concern.

North American Rockwell report SD 70-557-5,[12] dated 1970, documented several instances of excessive valve leakage in the Saturn S-II stage LH_2 systems where particulate contamination may have contributed to the failure. Forty-one Problem Action Records (PARs) related to contamination were reported during the processing of 15 S-II units at Seal Beach, the Mississippi Test Facility, and KSC. The failures due to contamination were primarily seal leakage above specification requirements, none of which would have resulted in a mission failure. Four specific incidents were reported of excessive leakage in LH_2 prevalve solenoids where teardown and analysis indicated that metallic contamination may have contributed to the failures. This report recommended that critical systems undergo a pneumatic purge (blowdown) to remove particles entrapped or generated during the assembly and test processes with collection of blowdown products on a 5-μm filter to verify completion. This report also recommended that particle contamination allocations be limited to only nonmetallic particles and fibers above 175 μm, and only nonmetallic fibers above 700 μm. These two limits, considered together, imply a maximum width for fibers of 70 μm. The rationale for distinguishing between metallic and nonmetallic particles was not explained. While five specific instances were noted of leakage in LH_2 prevalve solenoids due to metallic particles, the PAR history showed that approximately half of the contaminants identified as the cause of leakage were nonmetallic. The report and attached detailed particle analyses did not distinguish between metallic particles and metallic fibers. Based on this report, it appears that if all fibers are restricted to a maximum diameter of 70 μm, then it is not necessary to distinguish between metallic and nonmetallic fibers.

It is conceivable that a large quantity of hard metallic fibers, even if restricted to below 70 μm in diameter, could abrade the surfaces of seals and pumps. Contamination by a large quantity of any type of small, hard particles, such as sand, could also cause such abrasion. The requirement for "no silting," which was added to all MSFC-SPEC-164 particle classes in 1994 with revision B, is expected to avoid this scenario as well as ensure a valid inspection.

A problem report on "Engine LOX Pump Contamination"[22] (pp. 3-42 to 3-43) on Saturn S-II-12 identified metallic and nonmetallic fibers and shavings that were found during an engine modification not related to any failure. These particles included a stainless steel bristle with a diameter of 0.003 in and a length of 0.5 in (76 μm by 12,700 μm), a Kel-F® shaving 0.001 × 0.002 × 4 in (25 μm × 51 μm × 10 cm), a stainless steel fragment 0.001 × 0.005 × 0.030 in (25 μm × 127 μm × 762 μm), and a crescent of PCV (sic) such as Tygon® 0.005 × 0.25 in (127 μm × 6,350 μm). During a subsequent inspection of the LOX pumps on Saturn S-II-13, a "5 ½-in-long strand" (14 cm) of Kel-F with "irregular surfaces" was found in a LOX pump. Four of these five particles meet the definition of fiber. It was concluded in this report that none of these contaminants would be detrimental to stage performance and, beyond a source analysis to determine whether a component was chafing, no further action was recommended. No rationale was stated to support the conclusion that none of these contaminants would be detrimental to stage performance.

Other reports on space shuttle valve leakage noted the size of particle that appeared to be the cause of the leakage. One particle noted to cause leakage was a nitrile rubber particle 0.146 × 0.046 × 0.018 in (3,700 × 1,168 × 457 μm) located on a poppet face.[23] This particle far exceeded the maximum allowed size of 800 μm for the oxygen system.

Significant advances have been made in the understanding of seal design for cryogenic systems since the Saturn days. Given the known capabilities to design valves and sealing surfaces for these systems that will tolerate isolated particulate contaminants up to 400 μm in LH_2 systems and 800 μm in LOX systems, the presence of occasional fibers that are limited in these systems to a maximum diameter of 50–100 μm should be of little consequence. Based on the Saturn S-II experience, a maximum fiber diameter of 70 μm for all systems seems reasonable. No rationale has been identified to support different allocations for nonmetallic versus metallic fibers when such a diameter restriction is imposed.

7.3 Fire Hazards in Oxygen Systems

Most materials ignite more readily in enriched oxygen environments. Both organic and inorganic contaminants may present an ignition hazard in these systems. Extensive documentation is available on material selection and design principles for oxygen systems. American Society for Testing and Materials (ASTM) committee G04 on Flammability and Compatibility of Materials in Oxygen-Enriched Atmospheres, formed in 1975, has numerous publications on this topic including ASTM Manual 36, *Safe Use of Oxygen and Oxygen Systems*.[24] The NASA Materials and Processes Technical Information System contains an extensive database of test results for oxygen compatibility of materials.

Particle contaminants entrained in flowing oxygen may ignite on impact, presenting an ignition hazard in high pressure or high velocity oxygen systems, particularly in poorly designed systems. Accumulations of organic matter such as oil films can be ignited by particle impact, rapid pressurization, or other mechanisms. Acoustic resonance has also been shown to be capable of igniting an accumulation of particulate. Fibers must not present a greater ignition hazard than either an impacting particle or an accumulation of ignitable organic residue or particulate.

7.3.1 Particle Impact Ignition and the Kindling Chain

When a particle impact occurs within an oxygen system, the localized heat of ignition must be sufficient to ignite the impacted material in order to cause a system hazard. This cascade of events is referred to as a kindling chain. The maximum allowable particle mass to prevent impact ignition is highly dependent on the design characteristics of the system and its operating pressures and velocities.

Particle impact has been studied for high-pressure GOX systems at NASA's Lyndon B. Johnson White Sands Test Facility. Similar studies of particle impact in lower pressure LOX systems have not been identified for this analysis. Studies of the conditions under which particle impact ignition of various target materials will occur in GOX indicate that such ignition will not occur at LOX temperatures or at the relatively low pressures and velocities found in LOX propellant tanks and feed systems. However, higher transient temperatures and velocities may occur with the presence of GOX during system fill and cooldown preflight where particulate impact ignition must be considered. Hundreds of successful tanking operations of the space shuttle and its associated ground support equipment (GSE) demonstrate that hazards are effectively controlled by particle limits of up to 1,000 μm in LOX propellant tanks and 800 μm in LOX feed and drain systems and GOX vent systems.

Studies of the ignition of metals by impact of low velocity[16] and high velocity[25] particles have shown that ignition depends on both the kinetic energy of the particle at impact and the heat of combustion of the particle. The localized heat generated by this impact must be sufficient to ignite the material impacted in order to initiate a kindling chain. With the possible exception of aluminum targets at high particle velocities, it appeared that ignition of the impacting particle was required in order to ignite the target. Higher system pressures, flow velocities, and oxygen temperatures increased the probability of ignition of the particle and target. It was also noted that although small particles were easier to ignite, a single large particle was more likely to ignite the target than a large quantity of smaller particles (ref. 16, p. 75).

An impacting fiber of the same composition and mass as an impacting particle should yield the same or lower kinetic energy and energy flux density. Benz et al. (pp. 32–33) noted that deformation of the target or particle on impact will reduce the heat energy of the impact.[25] A small diameter metal fiber, that could be expected to deform on impact, may be less likely to ignite a target than a metal particle of comparable composition and mass. Based on the formulas for the volume of a sphere versus the volume of a cylinder, a fiber with the worst case aspect ratio of 10:1 will have a length of 3.75 times the diameter of a particle of the same material to yield the same impact mass. Based purely on the impact mass equivalent to a 1,000- or 800-μm metallic particle, the maximum allowable metallic fiber length would be 3,750 μm in the tank and 3,000 μm in downstream oxygen systems. At the 10:1 aspect ratio, these fibers would be clearly visible as chips or shavings.

Most laboratory particle impact tests have used metal or oxide particles, impacting metal targets. In 1995, a report was published by Dees et al.[26] on an evaluation of polymer particles as an ignition source in oxygen. Particles of Teflon (PTFE), Vespel® SP-21, Kel-F 81, and Viton® A, materials commonly used in oxygen systems, were impacted against stainless steel targets. Both large (up to 2,000 μm) and small (250 μm) particles were tested at subsonic and supersonic velocities and a range of temperatures. No target ignitions were observed under any of the test conditions, including those known to ignite the target when the particle is metallic. In several cases, it was evident that the polymeric particle ignited but no ignition of the target occurred. It was theorized that the lower densities, lower yield strengths, and different burning characteristics of polymers result in lower kinetic energy and energy flux density transferred to the target than comparably sized metal particles. It has been generally accepted by the oxygen systems design community that "nonmetal particulate is not an effective igniter" (ref. 24, p. 25).

By comparing the volume and specific gravity of fibers versus metallic particles, maximum fiber sizes can be calculated that yield an equivalent impact mass. Using a round steel particle of approximately 8 g/cm^3 as a worst case particle, the most massive particle permitted in the tank is 4.2 mg, 2.1 mg in all other LOX system components.

The specific gravity of nonmetallic fibers ranges from 0.3 g/cm^3 for lightweight paper to 2.6 g/cm^3 for fiberglass. Carbon composite fibers fall around 2 g/cm^3. Clothing fibers range from 1.1 g/cm^3 for nylon to 1.5 g/cm^3 for cotton. Even using the specific gravity of fiberglass, which is inert and will not ignite, calculations based on equivalent particle mass yield absurdly large fibers of 4,700 μm (versus an 800-μm particle) and 9,000 μm (versus a 1,000-μm particle) at the 10:1 aspect ratio. If the fibers are restricted to a diameter <100 μm, as indicated by the calculations for critical orifice plugging, the risk of a fiber of any composition causing an impact ignition based on mass becomes insignificant.

It should be noted that particle impact ignition studies published in ASTM G04 committee Standard Technical Publications have focused on GOX systems, generally under elevated temperatures and pressures and at high velocities. LOX system components, which operate at much lower temperatures, pressures, and flow velocities than the test conditions, are considered to be far less susceptible, if at all, to particle impact ignition.

7.3.2 Ignition of Accumulated Fiber Mass

The potential for ignition of an accumulated mass of contaminants must also be considered when establishing an allocation for fibers. Fibers present within assembled fluid systems prior to system fill, if entrained in the fluid flow, will tend to accumulate on system filters if the fibers are longer than the filter orifice diameters. Wire mesh, used as filter media in oxygen systems, propagates combustion more readily than rods or plates of the same material. Testing reported by Stoltzfus et al.[27] has shown that, while combustion rates increase with pressure, stainless steel, low carbon steel, and Monel® 400 will propagate combustion in oxygen at atmospheric pressures. Stainless steel mesh has historically been used for flight oxygen filters in NASA propulsion systems.

Due to significant differences in system internal surface area and in operating pressures, temperatures, and flow velocities, accumulation of fibers in the LOX tank, LOX feed systems, and GOX systems (such as a GOX ullage repressurization loop) must be considered separately.

Test methods have been developed to evaluate the suitability of filter designs and materials of construction for use in high-pressure oxygen service. Recognizing that filters must continue to perform safely in the presence of contaminants, these tests used particles and oils as ignition promoters with adiabatic compression or particle impact as the ignition source. Barthelemy et al.[28] used adiabatic compression to ignite oil, which then ignited 1 g of 44 µm, 97% iron powder (hydrogen reduced), which was then ingested into the filter. Odom et al.[29] adapted ASTM Test Method G175, Standard Test Method for Evaluating the Ignition Sensitivity and Fault Tolerance of Oxygen Regulators Used for Medical and Emergency Applications, to test the ignition resistance of contaminated stainless steel and brass filters in high-pressure oxygen. The test contaminant was a mixture of aluminum powder and iron particles with a perfluorinated lubricant. Neither of these investigations tested fibers or particles alone, without an oil or lubricant, nor was sensitivity testing performed to determine the influence of different levels of contaminant on the combustion of the filter.

Sensitivity studies on the hazards of ignition of accumulated surface contaminants in oxygen systems have focused on NVR such as oils and greases in high-pressure GOX systems. These contaminants, if present in sufficient quantity at high oxygen concentrations, can be ignited by adiabatic compression or particle impact and promote ignition of the substrate.

Limits established in the industry for NVR in oxygen systems range from 1 mg/0.1 m^2 in NASA LOX and GOX systems[1,30] to 47.5 mg/0.1 m^2 in commercial oxygen systems.[2,8,31] MSFC-SPEC-164 permits up to 1 mg/0.1 m^2 of NVR in flight oxygen systems except for tanks. Up to 5 mg/0.1 m^2 of NVR is permitted in flight LOX tanks and in ground test systems operating below 5,000 psig. The original technical rationale used to establish these NVR limits in the 1962 baseline release of MSFC-SPEC-164 has not been identified. The NVR limits for flight vehicles have never been revised and are still applicable in MSFC-SPEC-164C. Since 1994 (rev. B), MSFC-SPEC-164 has permitted NVR as high as 20 mg/0.1 m^2, with approval of the Director of Safety, in ground test systems operating below 5,000 psig.

7.3.2.1 Ignition of Accumulated Fiber in the Liquid Oxygen Tank. If an allocation for fibers is established with a maximum size and a maximum quantity per square foot of surface area, then it is possible for this allowed background level of fiber to migrate and accumulate. The largest surface area where particulate could accumulate prior to being collected on a filter or ingested is within the LOX propellant tank of the main propulsion system. Assuming that fibers are present at the maximum size and quantity on all interior surfaces of the LOX tank and all of these fibers are swept to and collected on the tank sump filter face during system operation, then a worst case total accumulation on the filter can be calculated.

It has been suggested that the allocation for one particle, up to 2,500 μm, per square foot in the baseline release of MSFC-SPEC-164 may have been intended to accommodate the occasional fiber. This cleanliness level is now shown in MSFC-SPEC-164C as class I and does not distinguish between particles and fibers. Using this limit as the proposed allocation for fibers in the LOX tank, a worst case total accumulation of fibers 2,500 μm long by 50 μm diameter is <20 mg/0.1 m^2, based on the following assumptions:

(1) A 0.43-m- (17-in-) diameter filter screen (the space shuttle ET LOX screen) (0.185 m^2 (1.58 ft^2)).

(2) Particles are evenly distributed on a tank internal surface area of 372 m^2 (4,000 ft^2) (estimated space shuttle LOX tank internal surface area including baffles and orthogrid).

(3) Average fiber density of 1.6 g/cm^3 (the high end of common environmental fibers).

(4) Maximum fiber volume is 4.9×10^{-6} cm^3 (2,500 μm long × 50 μm diameter).

(5) All fibers from the tank surfaces become entrained in the flowing LOX during system operation and accumulate on the tank filter screen.

(6) Due to mixing during flow, the distribution of accumulated fibers on the filter screen is uniform.

(7) All fibers shorter than 800 μm and most fibers shorter than 1,000 μm, the diagonal measure of an 800-μm square mesh orifice minus 10% to account for the width of the fiber, will pass through the filter screen unhindered. Assuming that the internal engine filters are no more restrictive than the tank screen, these fibers will be ingested by the engine and burned with the propellants. No accumulation of these fibers will occur.

(8) Most or all of these fibers are nonmetallic. Metallic particles do not typically occur as fibers, and when they do, metal fibers <50 μm in diameter are not typically found in such long lengths. Reports of cleanliness inspection failures due to fibers during propulsion systems cleaning have been reported to be from clothing fibers or something similar (M. Campbell, ET Project, Lockheed Martin, MSFC-Michoud Assembly Facility, Private Communication, March 13, 2008, and J.H. McMillian, Chemist, InfoPro Corp, Propulsion Test Valve Lab, MSFC, Private Communication, March, 17, 2011) (see ref. 12, table 2-5).

Limiting the fiber length to 2,000 μm reduces this accumulation to <16 mg/0.1 m^2. Further limiting the maximum fiber size by limiting the maximum diameter to 40 μm reduces this accumulation to <10.3 mg/0.1 m^2.

If the fibers are metallic, with a density of approximately 8 g/cm^2, then accumulation on the filter of 2,500 μm × 50 μm fibers could reach 100 mg/0.1 m^2.

All of these scenarios exceed the current MSFC-SPEC-164 NVR limit of 5 mg/0.1 m^2 for LOX tanks. However, there are several mitigating factors to indicate that this level of accumulation on the filter is both highly unlikely to occur and, if it did, unlikely to ignite and initiate a kindling chain.

7.3.2.2 Mitigating Factors, Fiber Floating. Tests of the response of fibers of cotton, silk, linen, jute, wool, paper, polyester, nylon, and miscellaneous dryer lint in both LN_2 and LOX showed that all of these fibers float to the surface of the cryogen during fill of the vessel and tend to form clumps there.[32,33] It can be assumed that nonmetallic fibers present within the LOX tank and not adhered to the walls by another mechanism will float to the LOX surface during fill.

Fibers floating at the LOX/GOX interface are not in contact with a combustible substrate. Even if an ignition of these fibers was possible, the initiation of a kindling chain in this location is not credible. Furthermore, if the tank is drained and refilled prior to flight, these fibers will most likely be swept out of the tank and captured in the 175-μm GSE filters. Such LOX drain and refill cycles are not uncommon on the launch pad. Even if they are not removed in this manner, floating fibers can be expected to reach the tank screen only near the end of the stage burn, if at all, leaving almost no opportunity for a metallic particle entrained in the flow to impact and ignite the accumulated fiber in a location where a kindling chain could be initiated.

Metallic fibers are 5 times denser than nonmetallic environmental fibers. These fibers are not expected to float in the cryogen and therefore could potentially collect on the tank filter.

7.3.2.3 Mitigating Factors, Heat of Combustion. Heat of combustion data are used to evaluate the potential for a material, once ignited, to ignite surrounding materials. Materials with lower heats of combustion are preferred for oxygen service (ref. 24, pp. 27–37). Tests of promoted combustion by ignition of contaminants on metal surfaces have been performed using hydrocarbon-based oil films known to ignite readily in high-pressure oxygen systems.[34] These oils, such as mineral oil and hydraulic oil, have high heats of combustion as compared to common environmental fibers. The heats of combustion of various materials that constitute fibers, oils, and other types of potential oxygen system contaminants are shown in table 5.

Table 5. Heat of combustion of contaminants.

Material	Heat of Combustion (cal/g)
Stainless steel	1,850–2,000*
Cotton fiber	3,900**; 4,000***
Polyester resin	4,300***
Wood, pine	4,700***
Titanium	4,711*
Silicone grease, Dow Corning 7	4,800***
Wool fiber	4,900**; 6,350***
Silicone	5,400†
Polyester fiber	5,700**
Aluminum	7,425*
Carbon	7,835***
Nylon fiber, nylon 6/6	7,400–7,900**, ***
Esters	8,500–9,600†
Hydraulic oil, MIL-H-83282	9,800†
Hydraulic oil, MIL-H-5606	10,10†
Mineral oil	10,700–11,000***, †

* ASTM Manual 36, table 3-11[24]
** CSIRO fact sheet[35]
*** Lowrie, R., contains a compilation of data from other sources[36]
† Totten, G.[37]

The heats of combustion of common environmental fibers are 20% to 60% lower than the oils used to evaluate the risk of contaminant ignition in oxygen systems. Heats of combustion of metals found in oxygen systems are 25% to 80% less than these oils. This reduces the energy available to initiate a kindling chain.

Metallic fibers have comparable heats of combustion to nonmetallic fibers but are denser. If ignited, an accumulation of metallic fibers, particularly aluminum fibers, in a high-pressure system theoretically could release sufficient energy to initiate a kindling chain. The threshold fiber mass required to create such a hazard is unknown. Ignition studies of multiple particles have been performed by injecting 2–3 g of fine particles as small as 10 μm into flowing GOX upstream of a target.[16,25] Lower masses were insufficient to ignite the target. This is a much greater mass than the predicted 100 mg/0.1 m^2 of metallic particles. The study by Odom et al.[29] of promoted ignition of metallic filters used 350 mg to 3.5 g of mixed aluminum and iron in a thin layer of lubricant as the contaminant promoter. These ignition studies tested different scenarios than the ignition of fibers alone, accumulated on the target by another source.

7.3.2.4 Mitigating Factors, Low Temperature and Heat Removal. Within the LOX tank and feed system of a bipropellant propulsion system, the temperature and pressure conditions are considerably lower than those used to evaluate the risk of ignition of contaminants in oxygen systems. While LOX is at a concentration equivalent to GOX at a very high pressure, the temperature is much lower than found in GOX systems. Assuming that fibers distributed within a LOX system will accumulate on a filter during fluid flow rather than float to the LOX surface, the cryogenic LOX flow will rapidly remove heat generated by a possible ignition of these fibers, preventing the initiation of a kindling chain. This risk mitigation in LOX systems is discussed by Lowrie[36] (p. 7), and is supported by other industry tests referenced there.

The hardware that must be ignited by burning fiber has also been cooled by the LOX to a very low temperature. The effect of target temperature on target ignition by an impacting particle was studied by Benz et al.[25] (figs. 7–9). In those studies, no ignition of the target was observed below about 390 K. At lower system pressures, no ignition of the target was observed below about 500 K. The scenario where a particle might impact an accumulation of fibers on a filter is only credible during LOX flow when the filter (target) is at a very low temperature.

7.3.2.5 Mitigating Factors, Contaminant Geometry. Lowrie also mentions the influence of geometric conditions on heat transfer of an ignited promoter to the other material. To initiate a kindling chain, the ignited contaminant must transfer sufficient heat flux to ignite the surface on which it resides. Most fiber materials have densities, discussed above, which are higher than mineral oils or hydraulic oils. The density of these oils is typically 0.7 to 0.8 g/cm^3. However, fibers do not accumulate in a continuous layer. The fibers that have the potential to accumulate on filter screens are very long and often twisted. Accumulations of fibers contain a considerable amount of free space that is expected to both dissipate heat to the LOX and reduce the physical contact between the fibers and the substrate, reducing heat transfer to the substrate material.

Furthermore, as discussed in the section above on particle impact ignition, nonmetallic particles have been shown to be incapable of transferring sufficient heat flux to substrates during impact ignition to initiate a kindling chain. The lower yield strengths and the burning characteristics of polymers that are theorized to contribute to lower kinetic energy and energy flux density transfer to the target during impact can also be expected to limit the transfer of heat flux from the ignition of an accumulation of nonmetallic fibers to the filter screen substrate.

7.3.2.6 Mitigating Factors, Conservative Nature of the Existing Nonvolatile Residue Limit. The technical basis for the 5 mg/0.1 m^2 limit for NVR in LOX tanks, established in MSFC-SPEC-164 in 1962, has not been identified. It has been suggested that this NVR limit was the best that could be achieved and verified at that time on such a large surface area. More recent testing (see ref. 34) has shown that hydrocarbon-based oils could be ignited in GOX by rapid pressurization at levels as low as 6 mg/0.1 m^2 (65 mg/m^2). However, this reference also reported that none of the ignitions observed during testing, even at the very high NVR levels of 300 mg/0.1 m^2 (3,200 mg/m^2), led to an ignition of the stainless steel tube used as the test article. The author cautioned that other substrate materials, such as nonmetals, may ignite under these conditions.

Werley, in the paper "Oil Film Hazards in Oxygen Systems," summarized oil film ignition data from a number of earlier sources.[38] One of the quoted NASA sources (C.J. Bryan, "Final Report on the Effect of Surface Contamination on LOX Sensitivity," KSC Letter Report MTB 306-71, 1971 (a copy of this secondary source has not been located)) stated surface contamination limits for Dow Corning 704 silicone oil (a highly reactive oil) that resulted in reaction of a substrate during

LOX mechanical impact tests at 98 N-m of energy. This source reported no reactions on aluminum 6061-T6 below 43.2 mg/0.1 m^2 and no reactions on Teflon below 21.6 mg/0.1 m^2. NASA launch vehicle LOX tank screens have used aluminum alloys and 300-series stainless steel for the frames and 300-series stainless steel for the filter mesh.

These reports indicate that the general NVR limit of 5 mg/0.1 m^2 in LOX tanks is very conservative. If fiber accumulation can be compared to NVR as an ignition promoter, then ignition of the aluminum and stainless steel tank filter screens by fibers at accumulated levels equal to or below 20 mg/0.1 m^2 is highly unlikely.

7.3.2.7 Mitigating Factors, No Credible Ignition Mechanism. For a fire to occur in the LOX tank there must be a credible ignition mechanism. ASTM Manual 36 lists the following 12 ignition mechanisms that have been known to cause fires in oxygen systems: particle impact, heat of compression from rapid pressurization, flow friction, mechanical impact, friction, fresh metal exposure, static discharge, electrical arc, chemical reaction, thermal runaway, resonance, and external heat. Some of these mechanisms are poorly understood and this list of mechanisms may not be complete (ref. 24, pp. 9–15).

As noted above, particle impact does not appear to be a credible ignition source in LOX. GOX will be present at the expected fiber accumulation location, the tank filter screen, during the beginning of the fill of the LOX tank, as boil-off from the LOX. Fluid velocity is insufficient at this time to support a particle impact risk. The LOX tank is purged with nitrogen prior to LOX fill.

Rapid pressurization and resonance sufficient to ignite contaminants are not credible within the large volume of the LOX tank. No materials are present that react chemically or exothermally in LOX or ambient temperature GOX. The LOX tank filter screen assembly contains no moving parts to generate friction heat. Static discharge, electrical arc, and external heat are precluded by design and operational precautions as a general safety measure.

Current theory indicates that flow friction can occur above 3.4 MPa (500 psi), which is about 4 times the maximum design pressure of the LOX tank manhole seal and LOX feed line on the Ares I upper stage and more than 10 times the ambient service pressure. (Refer to MSFC’s flange seals, specification control drawing 97M28929 and detailed specification for LOX feed line, ARES-USO-DE-25178, rev. A.) Also, heat generated by friction during LOX flow will immediately be dissipated by the flowing cryogenic fluid.

Mechanical impact ignition with fresh metal exposure could potentially occur from a large foreign object falling onto the LOX tank skin or filter screen aluminum frame. This would need to occur at the beginning of LOX tank fill before sufficient LOX is present to buoy the falling object and dampen the impact energy. Foreign object debris (FOD) prevention measures, including tank FOD rolls—rotations of the tank during manufacturing to listen for and release loose objects—are used throughout vehicle processing to eliminate FOD. A LH_2/LOX vehicle stage also undergoes several rotations and moves between horizontal and vertical prior to a LOX fill. A loose item of sufficient mass to cause ignition escaping notice prior to LOX fill and dropping at just the right time is highly unlikely.

7.3.2.8 Conclusions on the Ignition Risk of Accumulated Fiber in the Liquid Oxygen Tank. The potential exists for fibers, present at the maximum allocation per square foot of surface area throughout a LOX tank, to accumulate on the LOX tank filter screen during system operation to a level that exceeds the 5 mg/0.1 m^2 NVR limit in the tank. If one fiber up to 50 μm in diameter and 2,500 μm in length is permitted per square foot of tank surface area, nonmetallic fiber accumulation could be as high as 20 mg/0.1 m^2 in the filter screen. Metallic fiber accumulation could be as high as 100 mg/0.1 m^2. This is not a credible fire risk, however, for the following reasons:

(1) Laboratory tests indicate that nonmetallic fibers will float and accumulate at the LOX/GOX interface during ground fill rather than accumulating in on the tank filter screen during operation. Fibers accumulated on the LOX/GOX interface do not pose a credible fire risk because there is no ignition source in this location or opportunity to initiate a kindling chain.

(2) Should fibers accumulate on the filter screen during system operation, several mitigating factors indicate that an ignition of these fibers is highly unlikely due to the lack of a credible ignition source.

(3) Should an ignition occur, the ignited fiber mass is unlikely to transfer sufficient heat flux to ignite the filter material. Due to the number of variables and the lack of test data on the ignition of fiber accumulations in LOX or GOX, an acceptable threshold of accumulation is difficult to determine. Test data on the ignition of oil films in high-pressure oxygen systems indicate that the threshold to initiate a kindling chain reaction in a LOX tank is well above 20 mg/0.1 m^2. Other factors, such as the heat sink of flowing LOX and cryogenically cooled metal surfaces, and poor fiber contact with the substrate to transfer heat, are also expected to reduce the probability of transferring sufficient heat flux to ignite the filter material.

It should be noted that this analysis assumes an even initial distribution of fibers throughout the tank. Given that environmental fibers have the tendency to entangle and form clumps that may lead to measurement error on large components, accumulations of fibers that are visible during inspections should not be permitted.

It should also be noted that nonmetallic fiber contamination originating from clothing or from the outdoor environment are both more likely to occur and more difficult to control than metallic fiber contamination. Detection of more than an occasional metallic particle or fiber within a flight system is a potential indication of hardware damage or defect and should trigger a source investigation.

7.3.2.9 Ignition of Accumulated Fiber in Other Liquid Oxygen System Components. It is assumed that most fiber contaminants that pass through the LOX tank filter screen will also pass through downstream filters and orifices to be eventually ingested and burned by the engine. The fiber mass that is available to be accumulated on a filter is dependent on the internal surface area between the upstream filter and the downstream collection point.

Concept architecture for the future Space Launch System indicates that the largest downstream surface area in the LOX system is driven by the surface area of the oxidizer feed line. With a LOX tank mounted above the LH_2 tank, the feed system could be as long as 46 m (150 ft). Multiplied by the circumference of a feed line diameter of 0.3–0.5 m^2 (1–1.5 ft), the estimated internal surface area is 46–70 m^2 (500–750 ft^2); one-fifth to one-eighth the surface area of the tank. Potential fiber accumulation is reduced proportionally to roughly 4 mg/0.1 m^2 of nonmetallic or 20 mg/0.1 m^2 of metallic fiber. This assumes a single feed line with end point distribution to the planned five SSME-derived engines. Multiple feed lines will further reduce the potential accumulated mass.

Operating parameters for the SLS LOX feed system components are expected to be similar to the Ares I upper stage LOX parameters. These systems had maximum design pressures under 125 psia with nominal operating pressures under 50 psia and flow velocities <15 lbm/s. Given these operating conditions and a lower potential accumulation, the fiber limits allocated for the LOX tank should be acceptable for downstream LOX components as well. However, a system analysis should be performed to verify that transient high pressure or high temperature GOX will not occur in regions of the LOX components where fiber accumulation may occur.

7.3.2.10 Ignition of Accumulated Fiber in Gaseous Oxygen System Components. The potential risk of promoted combustion from accumulated fiber contamination in locations where GOX may be present is less clear. While substantial test data are available regarding the risks of particle impact ignition of metal and nonmetal substrates, no test data on accumulated particulate or fibers as an ignition promoter has been identified. Colson et al. have reported fires in oxygen system filters under conditions of high velocity, particle impact, and excessive contamination.[39] Monitoring of pressure drop and maintenance at regular intervals is recommended for all industrial oxygen systems. While this publication notes that particles, dust, and debris trapped on filters can ignite when ignition conditions are met, very little data are available to establish safe thresholds for maximum accumulation, dependant on particle or fiber size and system parameters such as pressure, velocity, temperature, and configuration.

A related earlier publication by Fano et al. noted that the auto-ignition temperatures of metals in powder form are much lower than in bulk materials, and that smaller particles may ignite larger particles which may in turn ignite bulk materials.[40] However, this and other sources have indicated that to initiate a kindling chain, the particle(s) must be ignited prior to impacting the target.[16,40] Particle ignition in tests reported by Williams et al. did not occur at velocities <45 m/s, independent of pressure between 2 and 30 MPa.[16] These conditions are much higher than typically found in LOX propulsion systems upstream of the engine and are not found in the tanks.

Within propulsion system components where GOX is present at temperature, pressure, and velocity conditions known to ignite particulate, accumulated metallic fiber could potentially serve as an ignition promoter. It is unlikely that nonmetallic fibers limited to less than one fiber per square foot, with a maximum dimension of 50 µm diameter by 2,500 µm long, could provide a sufficient accumulated combustion mass to create a hazard.

7.3.3 Conclusions on Fibers as Fire Hazards in Oxygen Systems

When fiber size is limited to below 50 µm in diameter, and quantities are limited by the "no silting" rule to prevent gross presence in the flowing oxygen, fibers of any composition do not present an impact ignition hazard. When quantities and size are further restricted to limit accumulation on filters, the credibility of fibers creating a fire hazard by impact ignition is even lower.

An allocation for fibers in LOX tanks and downstream LOX components, when limited to one fiber/0.1 m^2 with maximum dimensions of 50 µm diameter and 2,500 µm long, does not appear to present a credible fire risk. There does not appear to be any rationale to require a distinction between metallic and nonmetallic fibers. However, the LOX system design should be analyzed to verify that transient GOX will not occur under temperature, pressure, and velocity conditions sufficient to ignite a stray particle contaminant that might ignite an accumulation of metallic fiber.

Insufficient data are available to fully assess the potential fire risk from the ignition of an accumulation of metallic fibers within a GOX system, such as an oxidizer tank repressurization system, under high temperature, pressure, or velocity conditions. Limited testing by Odom et al. has shown that accumulated metallic particulate may contribute to ignition of stainless steel filter media in GOX even under standard atmospheric pressures.[29]

8. RESULTS

8.1 Fiber Size and Quantity Limits

Based on the analyzed risk scenarios, fiber length limits larger than the established particle size limits should be permissible in LH_2 and LOX propulsion systems and associated GSE and test systems. Several of these scenarios require that a maximum allocation be established for fiber size and quantity. Fiber size limits derived from the identified risk scenarios are shown in table 6.

Table 6. Derived fiber contaminant size limits for identified risk scenarios.

Maximum Fiber Length Limit (µm) (Worst case fiber is a cylinder with length = 10 x diameter unless otherwise specified)			
	Particle Class		
Risk Scenario	**Class IV (400-µm Particle Limit)**	**Class III (800-µm Particle Limit)**	**Class II (Tanks) (700- and 1,000-µm Particle Limits)**
Critical orifice plugging or restriction	1,000 (50-µm maximum diameter)	2,000 (100-µm maximum diameter)	Same as downstream
Equivalent surface obscuration	1,120	2,240*	1,960*/2,800*
Equivalent surface obscuration 100-µm maximum diameter	1,256	5,024	3,847/7,850
Equivalent surface obscuration 50-µm maximum diameter	2,512	10,048	7,693/15,700
Downstream filter obscuration from fibers bypassing the tank filter	NA	NA	50-µm diameter x 2,500 (fuel) 100-µm diameter x 5,000 (LOX)
Valve seal leakage	70-µm maximum diameter No clear length limit	70-µm maximum diameter No clear length limit	70-µm maximum diameter No clear length limit
Equivalent particle impact ignition mass	NA	3,000*	3,750* (LOX only)
Particle impact ignition by nonmetallic fibers	NA	No limit	No limit
Accumulated mass of 50-µm-diameter metal fibers limited to 100 mg/0.1 m^2 in tank/20 mg/0.1 m^2 downstream**	NA	2,000 (two fibers/0.1 m^2) LOX only GOX limits TBD	2,500 (one fiber/0.1 m^2 in tank)

*At the maximum 10:1 aspect ratio, these particles would be clearly visible during visual inspection.
**Yields an accumulated mass of nonmetallic fibers of 20 mg/0.1 m^2 in tank/4 mg/0.1 m^2 downstream.

Several of the above scenarios indicate that a width restriction on fibers is required. To minimize the risk of orifice plugging in LH_2 systems, prevent leakage of valve seals, and minimize the risk of accumulated combustible mass in LOX tanks, a maximum fiber width of 50 µm is advisable in both systems. With this width restriction imposed, it is not necessary to distinguish between metallic and nonmetallic fibers in the fuel system or in the LOX tanks. In regions of the oxygen system where GOX may be present, an analysis of pressure, temperature, and flow velocity conditions, including transients, should be performed at potential accumulation points to determine whether fibers can be tolerated.

Assuming a maximum fiber diameter of 50 µm, the maximum fiber length in the LH_2 downstream systems should be 1,000 µm. This is based on plugging of a critical orifice in the engine by a combination of a twisted fiber and particles. The maximum fiber length may be increased if the critical orifice is determined to be larger than assumed for this analysis.

While these calculations do not point to a quantity limit for fibers between 400 and 1,000 µm in length, some limit would seem prudent to limit the risk of restriction of a critical orifice or internal engine filter from an accumulation of these smaller fibers from the feed system. The limits established in MSFC-SPEC-164 classes I, III X, and IV X of not more than five particles between 175 µm and the higher limit, applied to these intermediate fibers, should provide an equivalent level of protection from flow restriction.

The maximum fiber size and quantity in the downstream oxygen systems is driven by both oxygen system safety concerns and plugging of a critical orifice in the engine by a combination of a twisted fiber and particles. Limiting all fibers to a maximum diameter of 50 µm and a maximum length of 2,000 µm will minimize the risk of critical orifice plugging. Limiting the quantity of fibers to not more than five fibers between 800 and 2,000 µm per 0.1 m^2 of sampled surface in these systems will limit the potential for accumulation of these fibers on a filter face or orifice to cause restriction. Given the limited surface area in the downstream systems versus the tanks, the potential for accumulation of fibers on a downstream system filter is about an order of magnitude lower. Limiting the quantity of these fibers to less than two per 0.1 m^2 will limit downstream accumulation on a system filter to <4 mg/0.1 m^2, a level considered by Pedley et al.[34] to be below the NVR contaminant promoted ignition threshold for even very high pressure GOX systems. This level of contamination can only be applied with confidence to LOX systems and to low pressure GOX systems where there is no credible ignition source at potential accumulation points.

The original MSFC-SPEC-164 upper limit of one particle up to 2,500 µm, when restricted to fibers as recommended by Rodebücher,[12] appears to be a reasonable limit for both the LH_2 and LOX tanks. In the LH_2 tanks, this limit is driven by filter screen restriction. In the LOX tanks, this is driven by a prudent approach to limit the opportunity for accumulation of potentially combustible matter on the filter screen. This will maintain the modified class II as a common requirement for both tanks.

8.2 Fiber Composition

As stated in section 2, cleanliness specifications that require the inspector to distinguish between metallic and nonmetallic fibers, or between flexible and nonflexible fibers as a proxy for metallic versus nonmetallic, create difficulties in the inspection process. Trained microscopists can determine whether a fiber appears to be metallic based on apparent reflectivity or a silvery appearance, or flexible based on an apparent twisting of the fiber, but these distinctions are somewhat subjective. Oxidized metallic whiskers may not be reflective. Some fibers, such as silk, jute, wood, or grass, are often straight and may not appear to be flexible. Definitive identification of metallic fibers versus nonmetallic fibers requires chemical analysis using expensive analytical methods such as scanning electron microscopy with energy-dispersive x-ray spectroscopy. Cleanliness specifications that require identification of contaminant composition should be avoided if possible.

The analyses for fiber size and allocation based on orifice plugging, filter restriction, and valve seal leakage do not require a distinction between metallic and nonmetallic fibers when fiber diameter is limited to 50 μm. These are the only considerations that apply to the fuel system; therefore, there is no need to distinguish between metallic and nonmetallic fibers in LH_2 systems and associated pressurization or pneumatic systems that do not interface with oxygen systems.

Industry test data have shown that metallic particles pose an impact ignition hazard in high pressure, high velocity oxygen systems whereas nonmetallic particles do not. Limitation of all fibers to a maximum diameter of 50 μm and maximum length of 2,000 to 2,500 μm effectively limits the mass such that individual metallic fibers cannot cause an impact ignition. Ignition of a limited accumulation of metallic or nonmetallic fibers inside a LOX tank appears highly unlikely due to the very low temperature, low tank pressure, relatively low velocities of potential impinging particles, and general absence of credible ignition sources. The relative risk of ignition in GOX of an accumulation of metallic versus nonmetallic fibers, where a credible ignition source may exist, is not clear. Allocations for any type of fiber that may permit accumulation in GOX systems must be approached with caution.

8.3 Measurement of Fibers

A specification that limits fiber size and quantity begs the question of how to measure the fiber. A circular cross section is assumed; therefore, two measurements are required for each fiber—the apparent diameter and the length of the fiber at full extension. Both manual and automated methods of sizing and counting particles have limitations when applied to fibers. Methods currently used to size and count particulate include automated measurement by light scattering, automated image analysis, and microscopic analysis.

8.3.1 Automated Measurement by Light Scattering

Automated devices that detect light scattering from particles are available for measurement in air, in liquids, and on surfaces. These devices can accurately count large quantities of particles within defined size bins but do not discern morphology or composition. These devices do not distinguish fibers from particles. Fiber size limits larger than the allowed particle size limits should not be permitted when using these devices as the sole measurement technique.

8.3.2 Automated Image Analysis

Image analysis systems are commonly used for sizing and counting of particles collected on a filter or a reference surface such as a fallout plate. Some sophisticated image analysis systems are capable of distinguishing between particles and fibers and sizing both types provided that the fibers are not overlapping. Automated image analysis may be used when combined with human observation of the counted images to verify that fibers in the field of view have been accurately interpreted by the automated system.

Automated image analysis systems are not generally able to distinguish between contaminant materials although some may be capable of distinguishing between particles of different colors.

8.3.3 Microscopic Analysis

A microscopist trained in the counting and sizing of particles can readily distinguish between particles and fibers and can easily measure the apparent diameter of fibers and the length of straight fibers. Measurement of twisted fibers is more complex. Length can be approximated by measuring the fiber in segments or, more accurately, by using an opisometer on a calibrated image of the fiber displayed on a computer screen. Either method should be sufficiently accurate for verification.

Fibers that are electrostatically charged or very twisted may stand away from the measurement surface making them difficult to measure. Wetting of the background surface may help to flatten the fiber to the surface for easier measurement, neutralize the static charge, and prevent loss of the fiber sample to local air currents.

9. CONCLUSIONS

System contamination by environmental fibers is a recurring challenge when manufacturing and testing large liquid bipropellant launch systems. An analysis was performed to determine whether fibers could be permitted in these systems beyond the established limits for particulate, to derive allocations for fibers if allowable, and determine whether there is precedent for such allocations. This analysis concluded that:

(1) There is technical justification to permit fibers longer than the maximum dimension for particles in both oxygen and fuel systems, with the restriction that these fibers be <50 µm in diameter.

(2) Maximum fiber length limits and quantity allocations can be derived to prevent plugging or unacceptable flow restriction in critical orifices and filters.

(3) There are numerous precedents, both historical and current, in NASA and commercial documents and specifications for the allocation of fiber limits as a discrete particle type in oxygen/fuel bipropellant systems. Fiber limits specified elsewhere are consistent with the limits derived by this analysis.

(4) It is not necessary to distinguish between metallic and nonmetallic fibers in fuel systems when the fiber diameter is limited to 50 µm.

(5) Fuel tanks require fiber limits by size and quantity to prevent excessive restriction of the tank feed filters and to prevent fibers that pass the tank filters from restricting downstream filters or creating a leak in a valve seal.

(6) Individual fibers limited to 50 µm in diameter, metallic or nonmetallic, do not pose a particle impact ignition hazard in LOX or GOX systems and are not expected to create a leak path in valve seals.

(7) In very large oxygen system components, such as main propulsion tanks and feed lines, there is a potential for even a low level of background fiber contamination to migrate and accumulate on a system filter to a potentially combustible level.

(8) The accumulation of a background level of either metallic or nonmetallic fibers, within limits to prevent filter restriction, does not pose an ignition risk in LOX tanks or downstream LOX components due to the lack of a credible ignition source and, if ignited, insufficient heat flux under low LOX temperature, pressure, and flow velocity conditions to initiate a kindling chain.

(9) An assessment of ignition mechanism and kindling chain is required for regions in the propulsion system where GOX may be present at elevated temperatures, pressures, or flow velocities

to evaluate the risk of ignition of an accumulation of fibers. However, insufficient data exist to evaluate the potential for an ignition source, such as a particle impact, to ignite an accumulation of fibers that in turn ignites a filter. This kindling chain scenario has not been tested. Threshold sensitivity of filter media to promoted ignition by an accumulation of fiber also has not been tested.

(10) The analyses for maximum fiber size and quantity are based on available design data from the Saturn V, space shuttle, and Ares I launch vehicles. Different engines may have different critical orifice sizes and filter designs that may require different size limits and quantity allocations for particles and fibers.

10. RECOMMENDATIONS

10.1 MSFC-SPEC-164 Particle Limits

To reduce manufacturing costs and schedule impacts driven by recleaning due to fiber contamination, the particulate cleanliness requirements in MSFC-SPEC-164 for propulsion systems may be relaxed to permit fibers up to 50 µm in diameter, with limits on maximum length and quantity. Recommended fiber allocations for MSFC-SPEC-164 particulate classes are shown in table 7. Also noted in table 7 are the propellant systems to which each class of requirement is applied.

Table 7. Recommended MSFC-SPEC-164 requirements for fiber contaminants.

Class	Particle Size (µm)	Maximum No. (per 0.1 m^2)	Fiber Length* (µm)	Maximum No. (per 0.1 m^2)
I	>2,500	0		
	700 < x ≤ 2,500	1		
	175 < x ≤ 700	5		
	No silting			
II (tanks)			>2,000	0
	>1,000	0	1,000 < x ≤ 2,000	1
	700 < x ≤ 1,000	40		
	175 < x ≤ 700	150		
	No silting			
III (LOX)			>2,000	0
	>800	0	800 < x ≤ 2,000	2
	No silting			
III X (LOX)			>2,000	0
	>800	0	800 < x ≤ 2,000	2
	175 < x ≤ 800	5		
	No silting			
IV (fuel)			>1,000	0
	>400	0	400 < x ≤ 1,000	5
	No silting			
IV X (fuel)			>1,000	0
	>400	0	400 < x ≤ 1,000	5
	175 < x ≤ 400	5		
	No silting			
V	Visually clean/no silting			

* Maximum fiber diameter 50 µm; fibers allowed only in liquid propellant tanks, and fuel and LOX components.
No fibers allowed in components that may be exposed to GOX without a risk analysis and approval of the procuring authority.

Table 7 includes no recommendation for class I. The current allocation for one particle up to 2,500 µm will accommodate the occasional fiber. Class I is no longer used for LH_2/LOX propulsion systems. Class III X with the added fiber allocation appears to be very similar to class I.

No change is recommended for class V, the visually clean inspection used for some nonmetallic components that cannot be flushed with a solvent for verification. Fibers limited to 50 µm diameter are very difficult to detect visually but may be detected under UV illumination. Ultraviolet is permitted in MSFC-SPEC-164 as an inspection aid. When UV is used, an occasional single, small fiber may be permitted. No visible accumulation of fibers is permitted.

10.1.1 Application to Future Vehicles

The assumptions used in this analysis to derive recommended fiber size and quantity limits should be evaluated for applicability to future liquid bipropellant propulsion systems. Engines other than the SSME and the J-2X require analysis for critical orifice sizes to determine the suitability of the MSFC-SPEC-164 particulate and fiber limits. Other parameters including system internal volumes and the presence of GOX subsystems or transients at high pressures, temperatures, or velocities may require adjustment to the allowable size or quantity of fibers.

10.1.2 Recommendations for Further Study

To understand the potential for accumulated fiber to act as an ignition promoter, testing is recommended. Both metallic and nonmetallic fibers in the range of 20 to 50 µm in diameter should be studied in concentrations of 20 mg/0.1 m^2 to 300 mg/0.1 m^2 on a test filter. Metal fibers tested should be composed of alloys used in the construction of propulsion system components. Nonmetallic fibers tested should be composed of common facility contaminants such as clothing fibers, paper and cardboard fibers, and carbon fibers used in the production of composites. Because NVR contamination is a known ignition promoter in oxygen systems, the potential synergistic effects of a combination of accumulated fibers and credible NVR levels should also be studied.

Tests should be performed to determine whether accumulated fiber lowers the threshold at which an understood ignition mechanism will ignite a target. Flight oxygen system filter materials should be the primary focus of this investigation. The test equipment and procedures used by Pedley et al.[34] to evaluate NVR contaminants as an ignition promoter or used by Odom et al.[29] to study filter design may be adapted to study this phenomenon.

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14. ABSTRACT

An analysis was performed to identify the engineering rationale for the existing particulate limits in MSFC-SPEC-164, *Cleanliness of Components for Use in Oxygen, Fuel, and Pneumatic Systems*, determine the applicability of this rationale to fibers, identify potential risks that may result from fiber contamination in liquid oxygen/fuel bipropellant systems, and bound each of these risks. The objective of this analysis was to determine whether fiber contamination exceeding the established quantitative limits for particulate can be tolerated in these systems and, if so, to derive and recommend quantitative allocations for fibers beyond the limits established for other particulate. Knowledge gaps were identified that limit a complete understanding of the risk of promoted ignition from an accumulation of fibers in a gaseous oxygen system.

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contamination, fuel contamination, particulates, liquid oxygen, liquid hydrogen, cryogenic rocket propellants

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