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CONTAMINATION CONTROL HANDBOOK FOR GROUND FLUID SYSTEMS

Prepared by
Hubert N. Allen
Victor A. DesCamp

Martin Marietta Corporation
12250 S. Highway 75
Denver, Colorado 80201

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JOHN F. KENNEDY SPACE CENTER
Design Engineering-Mechanical Systems Division
James R. McBee, Project Manager
Kennedy Space Center, Florida 32899

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16. Abstract

This handbook has been prepared to assist designers and other interested persons in dealing logically and intelligently with the problems posed by particulate contamination in ground fluid systems. Major topics discussed include: (1) the nature of contamination; (2) the effects of contamination; (3) the determination and attainment of required levels of initial cleanliness; (4) considerations during design; and maintenance of operational cleanliness levels.

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FOREWORD

This handbook was prepared by the Martin Marietta Corporation under Contract NAS 10-5935 "Cleanliness Level Requirements for Pneumatic and Hydraulic Components - Service Arm System, Complex 39" for the J. F. Kennedy Space Center of the National Aeronautics and Space Administration. The work was administered under the Technical Direction of the Design Engineering Directorate, Mechanical Systems Division, of the J. F. Kennedy Space Center with Mr. James R. McBee acting as project manager.

Prepared by: Hubert N. Allen
Victor A. DesCamp

Approved by: V. DesCamp
Victor A. DesCamp
Program Manager

NOTICE

SCOPE

This handbook has been prepared as a guideline to contamination control practices for those persons engaged in the design of aerospace ground fluid systems and portable equipment. The term "fluid", as used herein, implies either hydraulic oil, gaseous nitrogen, or gaseous helium. The handbook considers "contamination" to consist of solid particulate matter foreign to the fluid in which it is entrained; it does not consider impurities such as trace gases or volatile hydrocarbons. Water is treated separately where appropriate. The guidelines contained herein also apply in general to gaseous oxygen, gaseous hydrogen, fuels, and the cryogenic fluids; however, no attempt has been made to treat problems that are peculiar to these fluids. For example, hydrocarbon removal is quite important in oxygen systems; hydrogen demands special treatment for explosion-proofing; and the cryogenics present special problems such as valve stem sealing, moisture freeze-out, etc.

Further, the material presented herein is not intended for precision airborne equipment, servo valves, gyros, or air-bearings, or ground systems that interface with the vehicle. While the principles are applicable, the degree of control must be carried further than is normally necessary for ground systems.

No attempt is made herein to cover the design, construction, or operation of clean room facilities or equipment. Suggestions are presented in a brief manner concerning cleaning agents and methods, along with a discussion of the necessity of environmental control during assembly and maintenance operations.

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ILLUSTRATIONS

INTRODUCTION

The problem of specifying cleanliness requirements for aerospace ground equipment, both systems and components, is one for which very little uniformity of thought exists throughout the industry. This wide diversity of opinion extends from the designer who must exact high reliability requirements from his device, to the technician assigned the responsibility of attaining near-impossible levels of cleanliness. Often, the imposition of unnecessarily stringent cleaning requirements actually causes functional degradation of a component, which may or may not appear during acceptance testing. It is an absolute impossibility to attain and maintain a zero level of particulate contamination; yet all too often, attention is completely focused on contaminant removal, rather than on the conception of designs and procedures that are tolerant of a reasonable amount of foreign material. This attitude inevitably results in substantial cost increases for all phases from initial design through procurement, installation, operation, and maintenance. The important consideration is to control the level of contamination only to the point whereby it will not constitute a hazard or degrade the function of the product concerned.

With this concept as a goal, this handbook has been prepared to assist designers and other interested persons in dealing logically and intelligently with the problems posed by particulate contamination in ground fluid systems. Major topics discussed include (1) the nature of contamination; (2) the effects of contamination; (3) determining and attaining required levels of initial cleanliness; (4) considerations during design; and (5) maintaining operational cleanliness levels.

NATURE OF CONTAMINATION

Types of Contamination

The term "particulate contamination" as used herein encompasses the complete range of foreign materials found in fluid systems as well as ambient contaminants found in the environments in which the systems operate. Probably the most common materials encountered are metallic chips or slivers generated during various manufacturing processes; sloughed portions of rubber O-rings or plastic seats generated during component operation; grains of sand or dirt that enter the system when it is opened to the atmosphere, or that are contained in the fluid; and skin particles or cloth fibers that are generated during handling and installation operations. Other contaminants that occur but are less obvious are corrosion products; plating flakes; chemical products, such as thread lubricants or hydraulic oil decomposition residues; and paint flakes. Although not defined as particulate, water is also considered herein in connection with the formation of corrosion products. Examples of nonparticulate contamination, which are not discussed in this handbook, are chemical, such as trace gases, volatile hydrocarbons, etc, and biological, such as bacteria, fungi, spores, etc.

The particulate contaminants considered range widely in form or shape but are generally rough and irregular. Crystalline forms are sometimes found, as with silica or fluid decomposition products. The idealized, spherical particle is seldom seen, except perhaps where glass beads have been used in a manufacturing process. Fibers are commonly defined as having a length-to-width ratio of 10 to 1 or greater. The most undesirable contaminants are irregular, sharp-edged metallic or inorganic particles that erode surfaces, cut seals, score seats, and agglomerate readily, thus filling clearances or clogging orifices. Large numbers of fibers are also prone to form a mat which, in turn, traps smaller particles, thus clogging small passages and orifices.

Particle density will vary widely with respect to that of the system fluid. This density ratio, along with flow velocity, will govern whether contaminants will remain entrained in the fluid, or settle out and collect in traps and blind areas. In general, settling will predominate in gaseous systems (except for extremely small-sized particles), whereas in hydraulic systems entrainment is most likely to occur.

Sources of Contamination

There are three major ways by which contaminants may be introduced into, or developed within a system: built-in, generated, and external. All three are, to some extent, beyond immediate control of the designer; thus, it is imperative that their potential be recognized when evaluating the necessity for control equipment and procedures.

Built-in contamination is that which is created during manufacture and assembly. These may be classified as residual mold sand on castings, lapping compound, lathe and drill chips, grinding debris, weld splatter, damaged seal materials, and migration from filters. Such materials left over from manufacturing and assembly operations are among the most hazardous because they are usually hard and abrasive, and often (as with lapping compound) extremely fine and difficult to remove. Test bench fluids are a common source of contamination, not only because they tend to be overlooked on the assumption that they are clean, but because they usually involve the last operation before system activation.

Generated contamination is that which is created by actual operation of the system. This is normally debris generated by sliding surfaces, abraded seals, hose flexure, fluid degradation, and other chemical or physical processes. Flow across orifices and valve spool edges may generate contaminants caused by erosion or cavitation. Creation of such material will continue as long as the system is in operation. It is generally agreed that pumps are the major source of such contamination, followed closely by materials from damaged seals, sliding mechanisms, and other close-tolerance parts.

External contamination is that which finds its way into the system from the outside environment. The contaminant type and size will vary according to the system location and the proficiency of operating personnel. Most common types consist of airborne dust, sand, and moisture. Opportunity for entrance exists at relief valves, breathers, on exposed cylinder rods, and during sampling operations, make-up fluid addition, and maintenance operations. Condensation is a source often overlooked, as is the addition of improper fluid in hydraulic systems; both of these can cause fluid degradation.

Physical Relations

The designer should fully understand that all of the types of contamination described above are detrimental, and often exist as particles so small as to be invisible to the naked eye. The normal unit of measurement for particulate contamination is the micron (μ), 0.000001 meter. Thus,

1 micron = 0.0000394 inch

1 micron = 0.001 millimeter

or,

1 millimeter = 1,000 microns

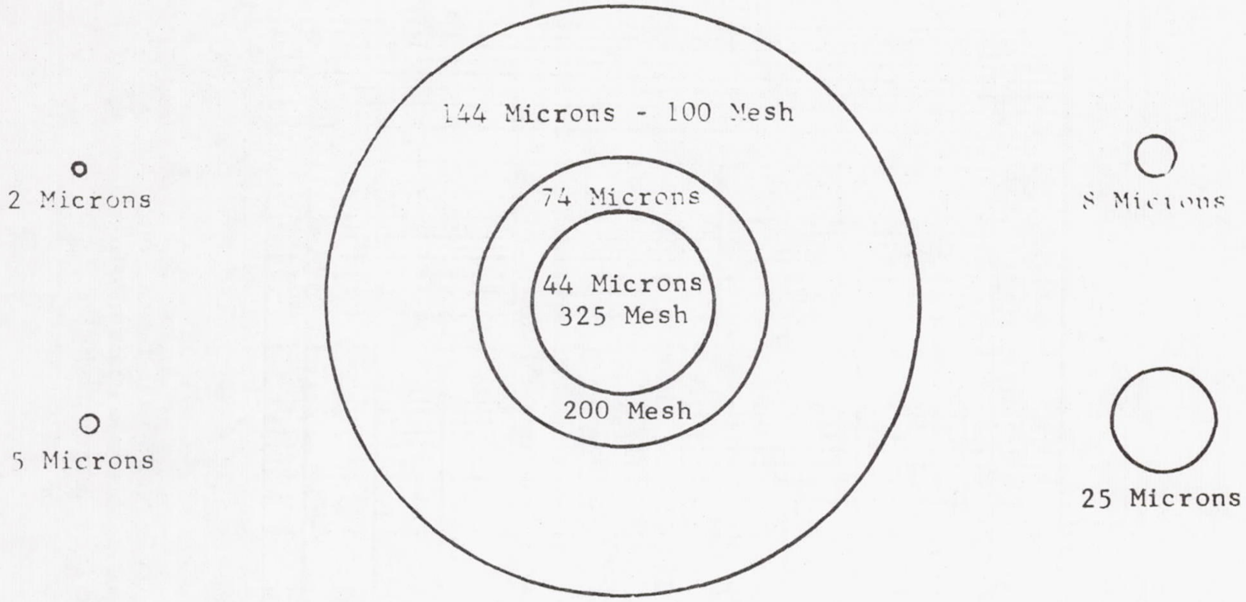
1 inch = 25,400 microns

The lower limit of visibility is commonly considered to be 40 microns; a human hair is approximately 100 microns in diameter. Figures 1 and 2 present conversion data for some common objects and materials. Figures 3, 4, and 5 show common shapes that particulate matter can assume.

When measuring particulate matter, the common practice is to gage and report the longest particle dimension. In ground fluid systems and components, the smallest particle of ordinary concern is 5 microns, and numerical control is usually attempted up to a maximum of 2000 microns. Fiber length limitations often extend to between 4000 and 6000 microns. Such particles are of course easily seen by visual examination, being several millimeters long. The emphasis of this handbook is on particulate matter of a size that requires microscopic techniques for identification.

Relative Size of Particles

Note: Magnification 500 times



Linear Equivalents

1 Inch	25.4 Millimeters	25,400 Microns
1 Millimeter	0.0394 Inches	1,000 Microns
1 Micron	$\frac{1}{25,400}$ of an Inch	0.001 Millimeters
1 Micron	3.94×10^{-5}	0.000039 Inches

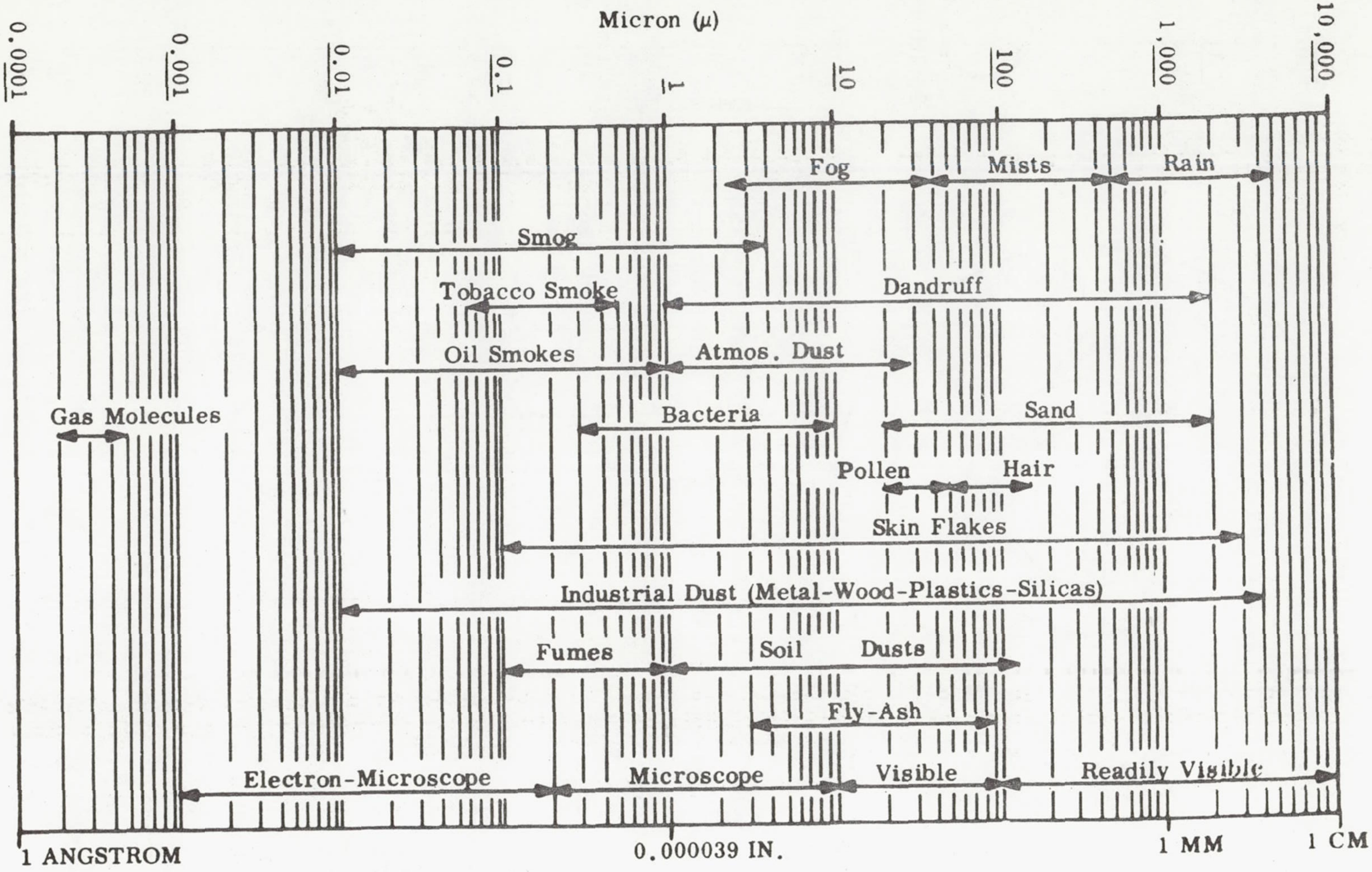
Relative Sizes

Lower Limit of Visibility (Naked Eye)	40 Microns
White Blood Cells	25 Microns
Red Blood Cells	8 Microns
Bacteria (Cocci)	2 Microns

Screen Sizes

Meshes Per Linear Inch	U.S. Sieve No.	Opening In Inches	Opening In Microns
52.36	50	0.0117	297
72.45	70	0.0083	210
101.01	100	0.0059	149
142.86	140	0.0041	105
200.00	200	0.0029	74
270.26	270	0.0021	53
323.00	325	0.0017	44
		0.00039	10
		0.000019	0.5

Figure 1 Size Conversion Chart



With this figure representing a particle 10μ in diameter, the larger figure represents the cross section of the average human hair 100μ. A major problem in contamination control is the tendency of the small particles to group and form larger particles.

Figure 2 Approximate Sizes of Common Particles

Shape	Appearance	Kind
Spherical		Vapor Pollen Fly Ash
Irregular or Crystalline		Mineral (Sand, Metallic, etc.) Cinder
Flakes		Mineral Epidermis
Fibrous		Lint Plant Fibre Animal Fibre
Floc		Carbon Smoke Fumes

Figure 3 Typical Shapes of Common Particulate Matter

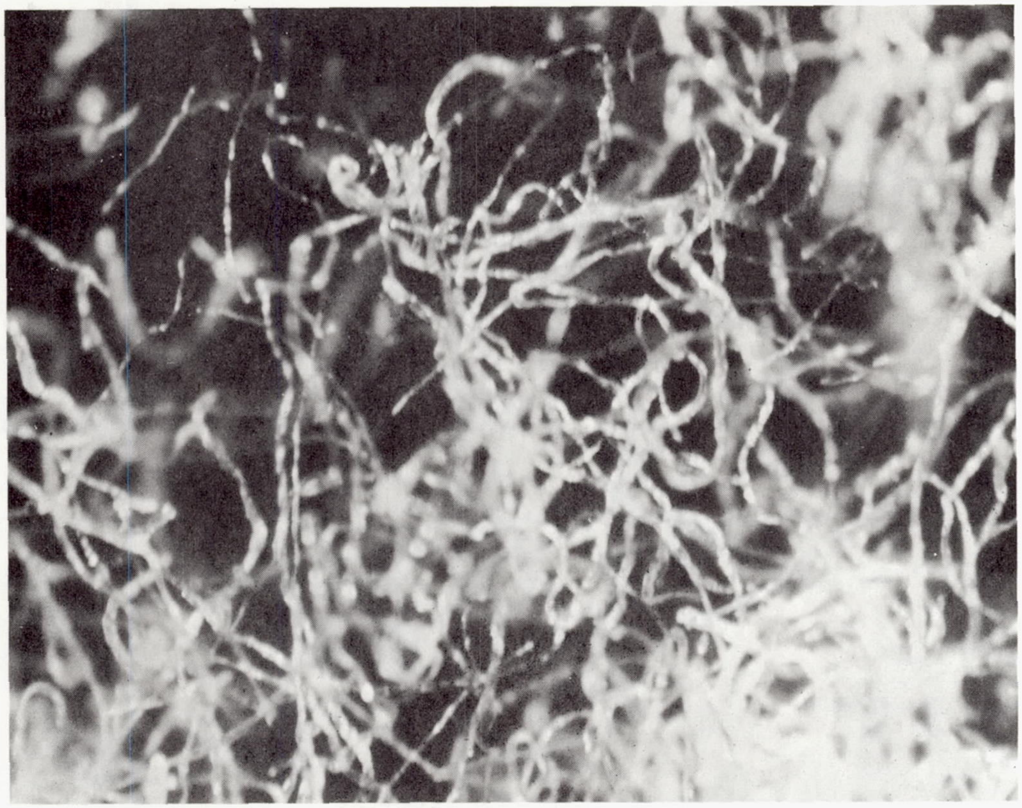


Figure 4 Cotton Lintner Fibers (100X Magnification)

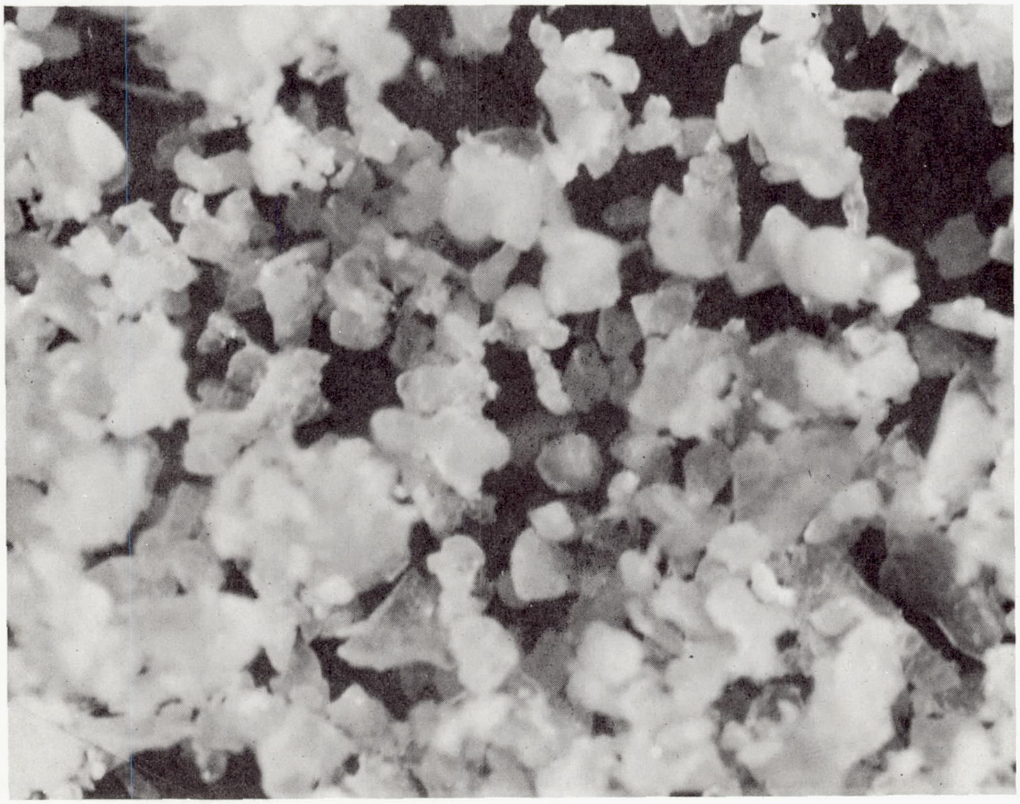


Figure 5 Teflon Particles (100X Magnification)

EFFECTS OF CONTAMINATION

Static Effects

The three most common effects of entrained particulate matter on static components are (1) clogged filters, (2) plugged orifices, and (3) leakage.

Clogged filters may occur where the filter is under-designed, in systems that contain extremely large quantities of particulate matter, or in systems over which poor maintenance procedures are exercised. Probably the majority of fluid systems contain filters that are effective down to the 10-40 micron range; thus, particles smaller than this size pass through the filter unaffected. Gross amounts of contaminants larger than this size will collect on the surface and ultimately block passage of the fluid to a point where the pressure drop of the filter is detrimental to proper system function. Such a situation usually occurs due to the presence of a severe contamination generator within the system, the addition to the system of uncontrolled make-up fluid, or fluid degradation resulting from chemical reactions. Proper design and specified maintenance procedures must be enforced to prevent this situation from occurring. The use of filters containing built in ΔP indicators is an aid that can be utilized in this respect.

The filtration efficiency of a filter increases as the fiber loads up with contaminant. Figure 6 shows the relation of filtration efficiency between a clean and dirty filter.

Plugged orifices may result from random large particles or fiber-matting in what may be relatively clean fluid. Orifices are usually of a size that will permit free passage of the smaller size particulate. Agglomeration of smaller particles in hydraulic systems can be a factor, especially in systems that see long inactive periods and use MIL-H-5606 fluid. This phenomenon is discussed in more detail in a later section of this handbook. Adequate filtration is the only solution to this problem, and even that cannot be guaranteed because fibers in particular may pass through surface type filters. Depth filters should be specified in especially critical applications (orifice sizes in the order of 0.010 in.).

Static leakage failures result from large hard particles becoming imbedded on the soft seat of a component, or scratching and gouging of metal-to-metal seats. O-rings and seals, damaged during assembly, are also a prevalent cause of static leakage.

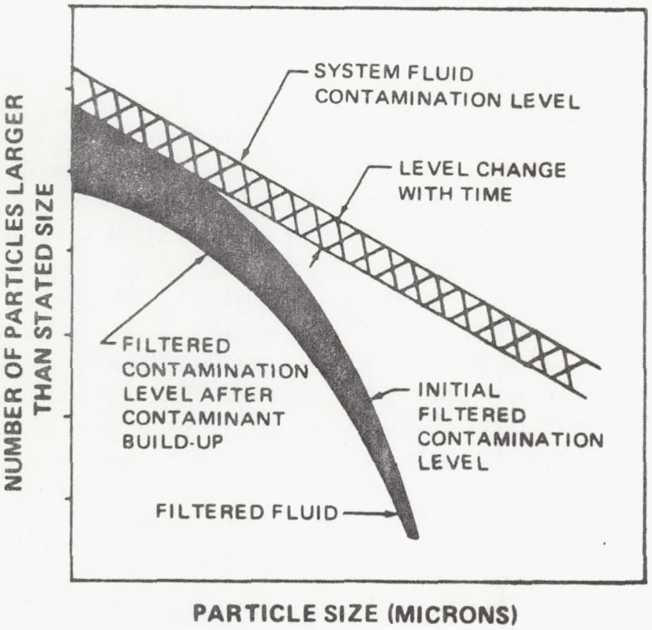


Figure 6 Filtration Efficiency

Filtration is usually an adequate answer to this problem. Large particles are generally the cause of static leakage failures. Many components contain relatively coarse, built-in filters to combat this problem. Especially critical components can also be protected by using small in-line filters, as long as pressure-drop considerations can be met.

Dynamic Effects

There are three common effects of entrained particulate matter on dynamic components: (1) stiction, (2) silting, and (3) wear.

Stiction is an acronym used to describe the phenomenon of a force increase necessary to impart motion to a sliding part, such as a piston. The word is derived from "sticking" and "friction" both of which imply dependence on the materials and fluids involved. The component clearances and the cleanliness level of the fluid are the determining factors related to stiction. The effect of the contaminant is to raise the force level necessary to impart motion. Extremely fine particles, those that easily pass through normal filters, are the contributing factor of stiction. Exceptionally fine filters, in the order of 0.5 to 2.0 micron rating, can be specified, but a better solution is the procurement of components that provide a wide margin of safety on actuating force provision.

Silting is a term that refers to the buildup of fine particles to the point of restricting or preventing motion. The tendency of a contaminated fluid to disrupt proper functioning of close-clearance components has been related to a "Silting Index". The Silting Index is determined by a specified procedure (ARP-788) that measures the pressure drop across a filter element and is a function of the fluid contamination. Procedure ARP-788 has been discontinued because of the poor correlation between existing agencies. Silting often results from heavy contaminant generators, or from chemical degradation of hydraulic fluid. It is usually only a problem in servo valves and similar parts containing clearances less than 0.0001 inch. Fine filters (0.5 to 2.0 micron) installed immediately upstream of the critical item, combined with strict fluid contamination control are necessary to prevent silting.

Wear of metering edges, seats, and orifices can result from the erosive action of contaminated fluid under conditions of significant flow quantities and velocities. This is particularly evident in high-velocity gaseous systems, and in cases where contamination generators are in action. Hard particles such as sand

and fine metallic particles generated by pumps and other sliding mechanisms are exceptionally abrasive when moving at high velocities. Erosion of soft resilient materials is less prevalent than on hard metal because the particles will bound off the resilient material without causing damage. Erosion of metal parts will also occur where the flow stream changes direction. The flow stream will change direction, but the particles with their velocity vector will impinge on the metal surface causing erosion. Components containing diaphragms and thin metallic bellows should receive consideration in this respect. The larger, heavier particles are less of a factor in erosion problems; as with stiction and silting, it is large quantities of fine particles that are detrimental. Wear caused by erosion can be minimized by increasing flow areas, decreasing flow velocities, and preventing direct impingement on metal surface. Fine filtration and frequent system fluid sampling are again necessary to eliminate and control the fine particles that are the source of erosion failures.

REQUIREMENTS FOR CLEANING

Problems of Unnecessary Cleaning

Unfortunately, when considering the cleanliness requirements of a component or system in the design phase, too many designers are inclined to "make it and keep it as clean as possible". This attitude reflects lack of professional responsibility by the designer and inevitably leads to the unanswerable question "How clean is clean?" The designer must ask himself, "How clean must this part be to function properly and reliably?", and it is his responsibility to determine realistic requirements for those features of the product that are critical. Unnecessary restrictions will result in high component costs, time delays, and can even be detrimental rather than beneficial to the deliverable item. The following criteria should be rigidly observed:

1) Do not specify a higher level of cleanliness than can be logically justified. Specifying an ultra-clean level just to be on the safe side, or calling for the cleanest level available at the facility, can have serious consequences;
2) Precision cleanliness should not become a requirement during the manufacturing cycle until it actually becomes critical;
3) Do not specify general terms such as "shall be free of dirt and particles" or "shall be assembled in a clean area". Quality Control personnel must have specific requirements to work to;
4) Do not automatically transpose requirements from one product to another. Each item or system should be evaluated in the context of its own application;
5) The total cycle of a component from manufacture, through cleaning, and to its final use point should be considered in contamination control. Anticipate conditions of acceptance testing, packaging, and extended storage. Much money is wasted and potential harm is done by inattention to details after the final cleaning and assembly operations.

More specific guidelines for specifying cleanliness requirements of components, systems, fluids, and environments are presented in the following paragraphs.

Component Requirements

The requirements specified for a fluid component not only affect its own reliability, but also reflect the characteristics of the system in which it must perform. Migration of contamination from one component may affect many others downstream. The primary reason for specifying a component cleanliness level is to attain an ultimately satisfactory system operating condition. Component levels should be more stringent than the desired system level. As a minimum, consideration should be given to the following items:

1) Fluid viscosity, density and velocity;
2) Reliability requirement and redundancy;
3) Statistical analysis of past performance;
4) Type of filtration in the system;
5) Minimum clearances and orifice dimensions;
6) Amenability to cleaning practices (complexity, calibration, compatibility to solvents, etc.);
7) Amenability to postassembly cleaning (after system installation);
8) Reactivity of cleaning residues with system fluid;
9) Necessity of lubrication for satisfactory operation;
10) Strength of positioning and actuating forces.

It is recognized that it may or may not be possible for the designer to accurately predict the point at which contamination will become a problem; he must, however, identify susceptible features and stipulate measures to assure their integrity until the end use. Whenever possible, proven standards of cleanliness should be specified. Good communications between Design, Manufacturing, and Quality Control are essential.

System Requirements

Establishment of system cleanliness requirements are dependent upon the function that the system performs. A system supplying gaseous nitrogen for cooling spacecraft navigational equipment must be much more carefully controlled as compared to one supplying hydraulic fluid for access platform actuation, or one providing deluge water. This usage also reflects upon component cleanliness requirements, and those of the fluid itself. Attention should be given to the following areas:

1) Particulate tolerance for the end use of deliverable fluids;
2) Practical extent to which flushing or other cleaning operations can be applied.
3) Advisability of cleaning with spool pieces prior to component installation;
4) Quality of filtration equipment available;
5) Comparison of contamination sensitivity of similar systems;
6) Reactivity of cleaning residues to system fluid;
7) Presence of potential contamination generators;
8) Effect of the system cleanliness level on component reliability.

Fluid systems require cleaning prior to placing the system in operation; and also when the system cleanliness level has exceeded specification because of component failure, wear, or because of the introduction of an incompatible fluid. Depending on the degree and type of contamination, there are two methods that can be used to clean a system:

1) Flushing with a new working fluid;
2) Chemical cleaning,
    a) Disassembly of the system and recleaning of all individual components,
    b) In-place cleaning of the entire system.

Flushing the system with its own working fluid is generally the most economical and compatible means of system cleaning, particularly for systems requiring less stringent cleanliness levels. Fluid system flushing is accomplished by draining the system, replacing filter elements, and then flushing the system with large quantities of working fluid. This procedure is acceptable for the removal of loose particulate matter, but cannot be used to dissolve and remove adhered and entrapped substances because of the limited solubility of most contaminants in the working fluids. Gross cleaning can be performed prior to assembling the system, as can localized procedures to dissolve and remove adhered or entrapped substances for which flushing would be ineffective.

Disassembly of a system and its components is expensive, but sometimes it is the only method by which the system can be fully cleaned.

In-place cleaning is accomplished by flushing or soaking the system with proper cleaning agents, followed by rinsing, purging, drying, and testing. This method has the advantage of not requiring disassembly and reassembly of the system. It has distinct disadvantages associated with its inability to remove all of the cleaning agents. Cleaning fluids will become trapped in voids and pockets, may cause stress corrosion, may be incompatible with seals, materials, or the working fluid, and may leave residues or films that may be a contaminant to the system or present a hazardous reaction with the working fluid.

Fluid Requirements

Fluid cleanliness refers to the condition of the fluid before it is placed in service; once the system has been activated, it is no longer possible to distinguish the fluid from the system in which it is contained. The following factors should be considered for unused fluid:

1) Particulate requirements of the system components;
2) Reaction of the fluid to construction materials and cleaning agents;
3) Cost of cleaning the fluid;
4) Accumulation of contaminants between the point of manufacture and the point of usage.
5) Silting characteristics of the fluid;
6) Fluid susceptibility to chemical degradation;
7) Filtration capability of the using system.

It is very important to make the distinction that new fluid is not necessarily clean fluid. Nearly all fluid procurement specifications permit designated quantities of both particulate and chemical contamination. New fluid requirements more stringent than this can be extremely difficult and costly to attain. The greatest simplicity and economy of system operation will be achieved by designing to existing fluid cleanliness specifications, or even lower if at all possible.

Environmental Requirements

The environment within which a fluid system is required to operate is a major source of contamination, yet the one over which the designer often has the least control; in fact, for major fluid systems, complete environmental control is not practical.

It is common practice of course to clean and assemble components in "clean rooms" or various other types of controlled environments; it is even possible to clean system plumbing in this manner, if relatively short lengths (and consequently many joints and increased leakage susceptibility) can be tolerated. However, these clean components and pipe segments must finally be assembled in the field. Maintenance operations must be performed, samples must be taken, and make-up fluid must be added. All of these operations require that the system be opened to the atmosphere to some extent, subjecting the system to airborne, generated, or built-in contaminatoon. The designer can only specify procedures that are aimed at reducing these deleterious effects to a minimum. The following recommendations may be of help:

1) Use of plastic "hoods" or "tents" with a low internal positive pressure will greatly reduce the entrance of sand and dust when a component must be removed and replaced in the field;
2) Washing of open fittings with a suitable solvent immediately prior to assembly;
3) Sparing use of thread lubricants. Teflon tape is satisfactory if properly used. If too much tape is used it will shred on the end of the fitting and become a system contaminant;
4) Specify procedures for precautions and awareness during sample taking, test equipment hookup, and make-up fluid addition;
5) Prohibit maintenance operations insofar as possible during rainy or windy weather, or while dirt-producing operations are being performed nearby.

Since the designer's ability to control the environment is often limited, it is to his advantage to encourage and promote training sessions or other educational techniques to acquaint operational and maintenance personnel with specific areas of system criticality regarding cleanliness. Personnel who will operate or maintain the system should also receive Contamination Control Certification. A much greater degree of cooperation can be anticipated when the underlying reasons for certain practices are well understood by those concerned. Figures 7 and 8 show some of the particle sizes and quantities that can be generated by the most ordinary, everyday types of activities.

Personnel Factors	Times Increase Over Ambient Levels for Particles 0.2 to 50 μ
Personnel-Protective Clothing (Synthetic Fibers)	
a. Brushing sleeve of uniform.	1.5 to 3
b. Stomping on floor - no shoe covering.	10 to 50
c. Stomping on floor with shoe covering.	1.5 to 3
d. Removing handkerchief from pocket.	3 to 10
Personnel per se	
a. Normal breath.	None
b. Breath of smoker up to 20 minutes after smoking.	2 to 5
c. Sneezing.	5 to 20
d. Rubbing skin on hands or face.	0 to 2
Personnel Movement	
a. Gathering together 4 to 5 people at one immediate location.	1.5 to 3
b. Normal walking.	1.2 to 2
c. Sitting quietly.	0 to 1.2
d. Dry box or enclosed box with absolute filter - no activity.	None
e. Dry box with hands inside.	0.01

Figure 7 Effects of Personnel

Activity	Approximate Size (Microns)
Crumpling or folding paper.	65
Writing with ball point pen on ordinary paper.	20
Vinyl abraded by a wrench or similar tool.	8
Rubbing or abrading an ordinary painted surface.	90
Rubbing an epoxy painted surface.	40
Handling passivated metals such as fastening materials.	10
Seating screws.	30
Sliding metals surfaces (nonlubricated).	75
Belt drive.	30
Abrading the skin.	4
Soldering (60/40 rosin flux cored solder).	3
Oil smoke particles.	0.1

Figure 8 Typical Sources of Particles

CLEANING TECHNIQUES

Ordinarily, the designer's responsibility does not extend into the process area where cleaning agents are utilized and cleaning methods are employed. However, a general working knowledge of these materials and processes is almost indispensable before intelligent decisions concerning product cleanliness can be made. Therefore, a brief treatment of cleaning agents and methods follows; for a more complete discussion consult Reference 2.

Cleaning Agents

Surface contamination can be removed in many different ways to suit various purposes. For example, a metal part may be wiped with a rag and considered visually clean; if it is to be plated, however, further chemical cleaning will probably be necessary; even then a residual oxide film may exist which requires an acid dip to create a condition of metallurgical cleanliness.

In the case of fluid systems and components, two main types of cleaning are utilized: (1) shop or gross cleanup, and (2) final or precision cleaning. Shop cleaning involves rough methods such as grit-blasting, abrasive tumbling, pickling and descaling, wire brushing, etc., and will not be given further treatment here. Final or precision cleaning involves the use of various chemical agents to remove the contaminant to a predetermined level. Some of these agents are detergents, soaps, acid or alkaline cleaners, solvents, or plain tap water. The choice of the agent to be used depends on several factors, some of which are important to satisfactory product function:

1) The agent must be capable of removing contaminants by dissolving them or washing them away. The choice of the cleaning agent must involve a knowledge of the nature of the contaminant, as a specific agent is required to remove a particular variety of soil;

2) The cleaning operation must not be detrimental to the basic product material. This implies that all materials of construction must be positively identified by the designer. Whenever possible, the agents should be inhibited or stabilized to prevent the development of corrosion along with the cleaning action. Proper consideration of compatibility will prevent such detrimental effects as tolerance reduction, hydrogen embrittlement, stress corrosion, and elastomer deterioration;

3) The agent must not leave film or residue on the surface that may later react with the operational fluid;

4) The agent must be amenable to filtration or other means of reducing its particulate count to a level lower than that required for the product being cleaned;

5) For maximum economy, the agent should be reclaimable to some degree.

Thoughtless use of cleaning materials is an area of negligence that can result in poor system performance or even structural failure. The designer should be thoroughly familiar with all materials and methods contained in any cleanliness specification that he calls out, in addition to the particulate levels that it requires (Figure 9).

Cleaning Methods

The manner in which a product is cleaned will depend to a great degree on three factors: size, ease of disassembly, and cleanliness level requirements. Throughout this discussion, it is important for the designer to remember that a particle count of the final rinse is not a measure of the amount of contaminant that may still reside in or on the product, but only a count of the particles that come out in the sampling fluid. More attention should be given to the cleaning processes used to clean a part than to a specific particle count.

Flushing - This is the simplest method and is most often employed for tanks, accumulators, and piping. The cleaning agent can be the operational fluid or a specific chemical; in either case it must be filtered or otherwise cleaned to a more stringent level than that required for the product. No disassembly of the product is required for this type of cleaning operation. The technique is to introduce a specified amount of fluid into the product and either allow it to pass out the other end, or drain it back out of the inlet. Better cleaning will be realized if the flush fluid is flowed at or above the flow rate that the component will experience in actual operation. If necessary, the process is repeated with fresh fluid each time until the required level of cleanliness is attained. If size permits, the part can be agitated or vibrated to assist in loosening the contaminant. This method presents two distinct disadvantages: (1) it is virtually impossible to ensure that all traces of liquid cleaning agents are removed from the product, thus posing possible corrosive problems; (2) the cleaning agent may remove lubricants that are necessary to successful operation of the product. For these reasons, this method is most successfully used with the system fluid as the flushing agent, and where relatively loose particulate requirements exist.

NOTE

(1) Symbols in the block denote a recommended process for the surface condition indicated, and will normally be accomplished in consecutive order from left to right.

*(2) Trichloroethylene shall not be used for cleaning elastomers.

		Precleaning Processes														
Material	Surface Condition	Mechanical Descale	Degrease	Alkaline Clean	Tap Water Rinse	Detergent Clean	Tap Water Rinse	Phosphoric Pickle	Tap Water Rinse	Chromate Dip	Tap Water Rinse	Pickle and Passivate	Tap Water Rinse	Demineralized Water Rinse	Drying	Preparation for Clean Room Entry
Aluminum, brass bronze, copper	Bare or machined, free of heat oxidation		X	X	X									X	X	X
	Anodized or chemical film coating		X		X	X								X	X	X
	Weld scale, corrosion, or heat oxidation	X	X	X	X									X	X	X
Stainless steel	Free of scale		X	X	X									X	X	X
	Weld scale, corrosion, or heat oxidation	X	X	X	X							X	X	X	X	X
Carbon steel	Free of scale		X	X	X					X	X			X	X	X
	Weld scale, corrosion, or heat oxidation	X	X	X	X			X	X	X	X			X	X	X
Non-metallic parts, elastomers*	As received					X	X							X	X	X
Electroplated parts and dissimilar metals	As received		X	X	X									X	X	X

Figure 9 Selection Chart for Cleaning Processes

Detail Parts - Cleaning of detail parts is probably the most common method employed for complex components. Here, the product is completely disassembled and each detail part is individually cleaned in the cleaning agent. Vibration, or ultrasonics will again enhance the cleaning operation. Cleanliness verification is accomplished with a filtered flush fluid. When performed in a controlled environment, this method is capable of attaining stringent cleanliness levels. The detail parts can be thoroughly vacuum or heat-dried to assure removal of all traces of the cleaning agent. This method also has two inherent disadvantages: first all the individual clean detail parts must of course be reassembled and even though this operation is performed in a clean room, contamination can be generated in many ways; screw fasteners must be installed, lubrication must be applied, O-rings must be inserted, etc. Thus, when the finished unit is completely reassembled, there is no real assurance that the particulate count remains acceptable. Secondly, most complex fluid components will be required to pass an acceptance or functional test, after cleaning, prior to leaving the manufacturer's facility. This obviously means hookup to a test bench and flowing of a test fluid. It is here that many components are contaminated far beyond the allowable limits established by the designer, unless adequate filtration is applied to the test fluid. Unless thorough attention is paid to all steps of the operation through assembly, test, and packaging, all the effort expended on cleaning the product may be voided.

Ultrasonic Cleaning - This is accomplished by immersing the part to be cleaned in a solvent solution that has a specific sonic energy applied to the solvent bath by transducers mounted in the cleaning tank. The sonic energy produces cavitation on the surface of the part that will loosen the contaminant. This method offers a distinct advantage in that it is capable of removing contaminant from crevices and blind areas. It is generally performed in a controlled area adjacent to the clean room and requires special equipment and trained operators. It is capable of damaging or destroying fragile equipment. Many different cleaning agents can be employed, along with varying temperatures and energy input levels. For a very complete description of this process, the reader is directed to Reference 2.

Vapor Degreasing Equipment - This is often used on parts that contain stubborn films or tightly adhered contaminants that would be difficult to remove by hand. Like ultrasonics, it is ordinarily used prior to the final detailed rinse if stringent cleanliness levels exist. It is not used in a clean room. Again, a large variety of cleaning agents may be used (Reference 2).

The designer should note that many of the agents used in the processes described above present hazard or toxicity problems, some of which are quite substantial. Specification of a particular agent may require safety procedures calling for special equipment or significant facility alterations. Thus, the design activity should not randomly call for specific agents without due consideration of existing facility capability.

FILTRATION

From the foregoing discussions it is obvious that sufficient anomalies exist in system cleaning techniques and the verification of cleanliness to preclude sole reliance on these methods for operational reliability. Good design practice therefore includes thoughtful provision of filtering devices in both liquid and gaseous systems. Filters in a system do present some limitations such as pressure drop and the requirement for maintenance of the filter elements. It is also possible for an inadequately designed or maintained filter to render a system inoperative by clogging and subsequent rupture of the element. Nevertheless, filtration is the best means of achieving reliable operation of critical fluid systems. The systems designer should therefore become familiar with the various types of filtration equipment available and utilize it to advantage in satisfying the contamination control requirements of his product. The following discussion highlights the most pertinent factors to be considered for meaningful filtration.

Rating Terminology

Filters are rated or classified according to the size in microns of the largest particle they will pass (or conversely, the smallest particle they will retain). Thus, a 10-micron filter will theoretically retain all particulate matter 10 microns in size and larger. Somewhat complicating this definition is the fact that two rating figures are sometimes presented; nominal and absolute. The absolute rating is the diameter in microns of the largest spherical particle that the filter will pass. Nominal ratings are generally interpreted as meaning the minimum size to which 98% of particulate removal may be expected. The terminology "nominal rating" has often been misinterpreted and now the trend is generally towards only specifying an "absolute rating". Another fact to consider is that the general industry practice is to rate filters based on liquids as the working fluid. A given filter element will trap particles down to a smaller size when the flowing medium is gaseous. (At least one manufacturer rates each of its elements according to liquid or gaseous service).

Filtration Techniques

Since rating implies particle size, it is thus interrelated to the definition of particle size. Since the vast majority of particulate matter is irregularly shaped, it becomes apparent that a filter may indeed pass particles, and especially fibers, which are larger in one or two of the dimensions than the absolute rating of the filter. The determining factor is the orientation of the particle at the time it meets the filter, which of course is purely random. This effect is most noticeable on <u>surface</u> type filters, wherein filtration is accomplished by impingement and retention of the particulate on a matrix of pores or opening on a single plane. To combat this effect, <u>depth-type</u> filters have been developed which, as the name implies, present a matrix of pores in series. Filtration occurs not only at the surface, but throughout the thickness of the media that presents a tortuous, circuitous path.

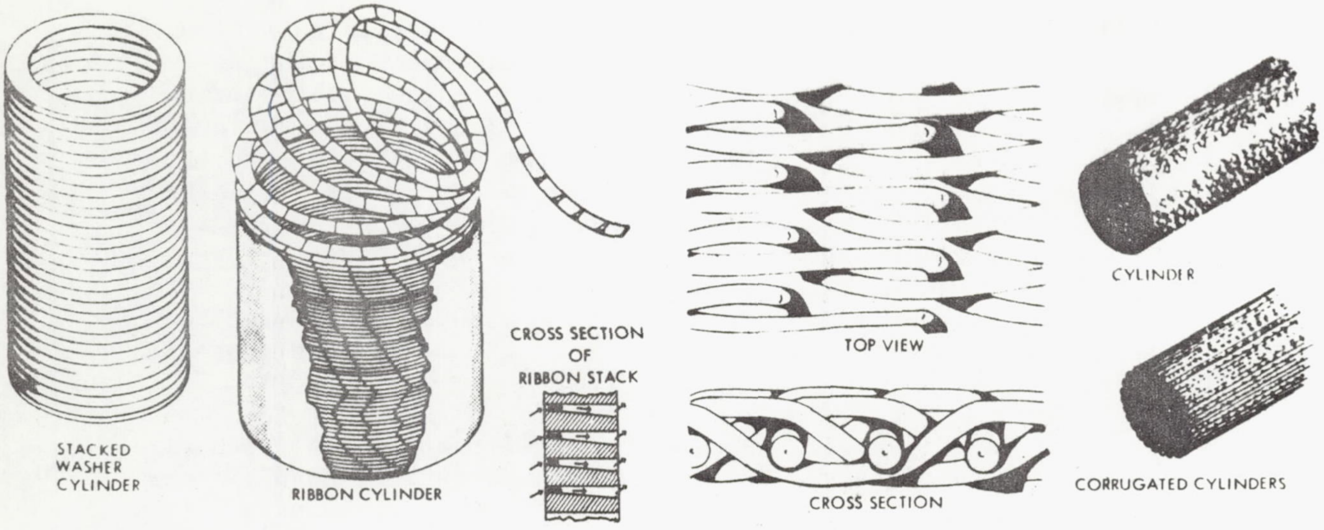
These two filtration techniques, surface and depth, each offer various advantages and disadvantages concerning such factors as pressure drop, cleanability, dirt-holding ability, efficiency, collapse pressure, media migration, maintainability, and cost. Due to the wide variety of equipment available, it is highly recommended that filter manufacturers be contacted during the design phase for assistance in technique and media selection.

<u>Filter Media Description</u>

The material from which the filter element is made is known as the media. Many different materials and construction techniques are available to meet various system requirements; some of these are pictured in Figures 10 and 11. A description of the major types is presented below.

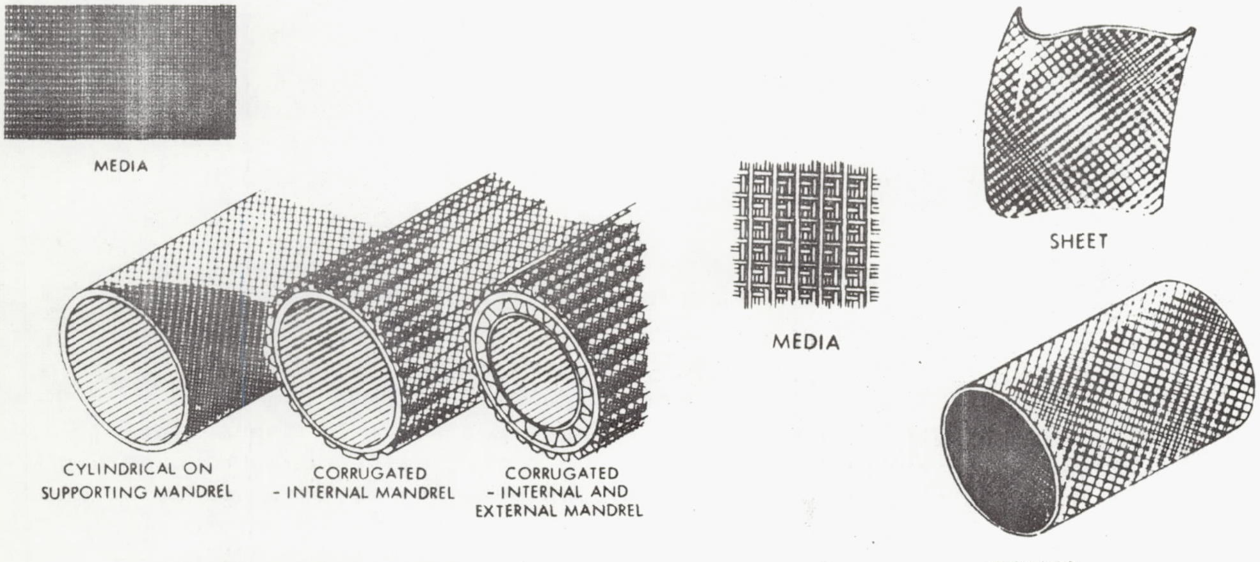
1) Woven wire mesh is produced on a loom in the same manner as conventional cloth materials. The opening is a square pattern and presents a straight-through path to the fluid. Twilled weaves (Dutch twill) that present a more circuitous path to the fluid are also available. These media are of the surface type. Since there is no mechanical bond between points of wire intersection, the mesh may distort and allow random passage of large particles. Initial cleanliness is difficult to obtain because contaminants are woven right into the mesh if not eliminated prior to manufacture. These contaminants will continually work loose (migrate) during the life of the element. The weave may also be sintered.

2) Wound wire mesh is similar to woven wire except that the cloth is formed by helically cross-winding wire on a mandrel. The wires are then sintered and the cloth is removed from the mandrel and either retained



Edge Filters

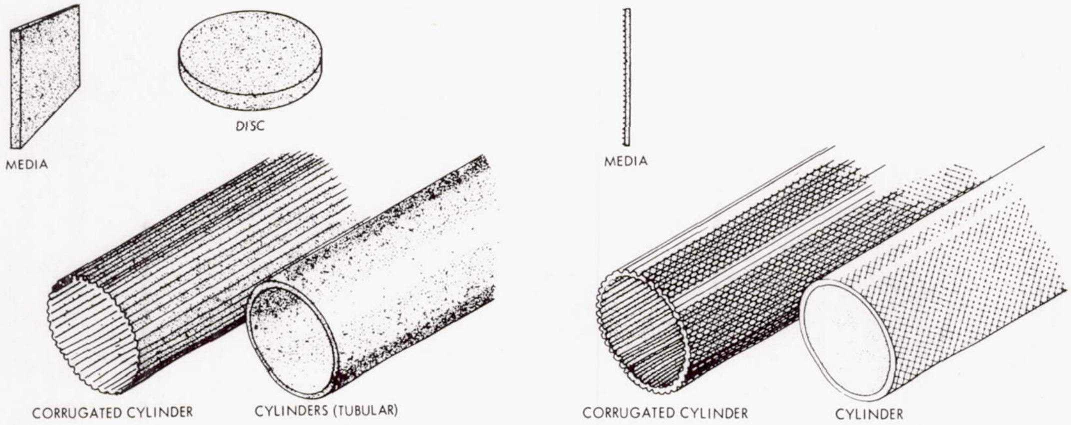
Dutch Twill Weave Wire Cloth



Woven Square Mesh Wire Cloth

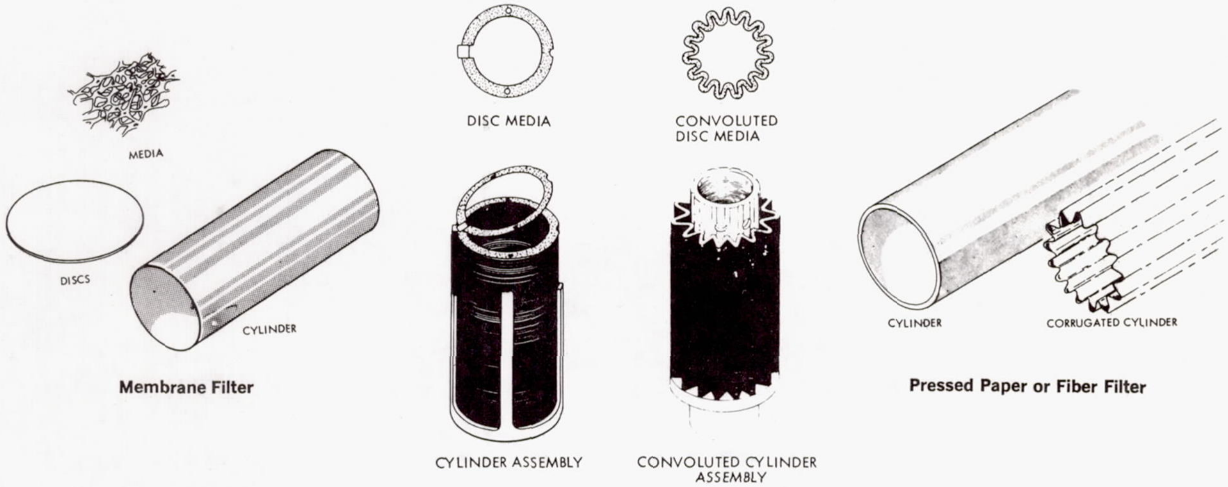
Woundwire Media

Figure 10 Metallic Filter Media



Sintered Porous Metal Filter

Composite Sintered Porous Metal with Wire Mesh



Membrane Filter

Etched Disc Filter

Pressed Paper or Fiber Filter

Figure 11 Filter Element Design and Material in cylindrical form or slit into sheet. These media are essentially of the surface type but do present some depth and are less liable to distort. Migration problems are similar to those of woven cloth.

3) Sintered metal filters are manufactured in a wide variety of forms by sintering a solid block of metallic powder. Bonding and structural strength may vary from poor to good. Initial cleanliness is difficult to attain and migration cannot be totally eliminated, even by plating. This is a depth-type element.

4) Composite sintered metal and wire cloth elements have been developed to obtain the depth characteristics of sintered metal while using the wire mesh as a backup to help reduce migration. It has been found, however, that initial cleanliness is quite poor and that migration from the metal/wire interface can be quite severe.

5) Edge filters are formed from stacked porous washers or from ribbon wound to form a hollow cylinder. The stack is mechanically compressed so that pore size will not vary. This is a surface-type element. Good initial cleanliness can be attained, and media migration is low. Size and weight can become excessive for some design applications.

6) Etched disk filters are similar to edge types except that each washer has one face chemically etched to create an intricate flow path, thus creating a depth filter. Initial cleanliness and migration characteristics are both quite good. Size and weight can be excessive.

7) Pressed paper or matted fibers are available in such forms as cylinders, discs, and corrugated shapes. Wide variation may exist in pore size and structural properties. Initial cleanliness is difficult to attain and migration will be present. Depth is present only to a limited degree.

8) Microcellular plastic filters are most often used for sampling apparatus and for filtering cleaning agents. They are surface-type filters consisting of a thin porous membrane wherein the size of the capillary pores can be quite closely controlled. Some available materials are cellulose esters, nylon, polyvinyl chloride and epoxy. Such membranes

are presently available down to the extraordinarily small size of 0.01 ± 0.002 micron and are used in sterilization applications. Initial cleanliness and migration tendencies are reported to be excellent. These are not generally available in sizes adequate for large continuous system flow applications.

Any selection of media material should be carefully scrutinized for compatibility with the operational fluid and with anticipated cleaning agents. The most common media cleaning techniques (where cleaning capability exists) are back flushing and ultrasonic.

Filter Case Design

The success or failure of a fluid filter depends to a large extent on the case design, primarily in the method of sealing the upstream face of the element from the downstream side. Any leakage across this interface will defeat the purpose of the filter. This interface is ordinarily a design feature of the various manufacturers, so that the system designer has a choice, but very little control. There are other design features, however, (Figure 12) that are often offered as options which may have applicability in certain places and should receive consideration by the system designer:

1) Dual-element filters consist of two elements of different ratings, one within the other, either of which is removable. A common rating for hydraulic service is 3 microns primary and 15 microns secondary (absolute). The major advantage of this configuration is that the primary element can be removed and replaced without disturbing the secondary element; thus, the system is not subjected to the atmosphere during filter maintenance. The secondary element is always functioning and provides redundancy in filtration.

2) Differential pressure indicators are available in the form of a colored button of some sort that pops up when the dirt accumulation on the element creates a pressure drop of a predetermined value across the filter. Such a device is a useful aid to maintenance procedures in systems that may see large amounts of contamination. They may be used, for example, downstream of a known contamination generator such as a hydraulic pump. It is possible for these devices to give a false indication, particularly in systems which may see short, severe pressure surges. If pressure indicators are used as a primary indication for filter

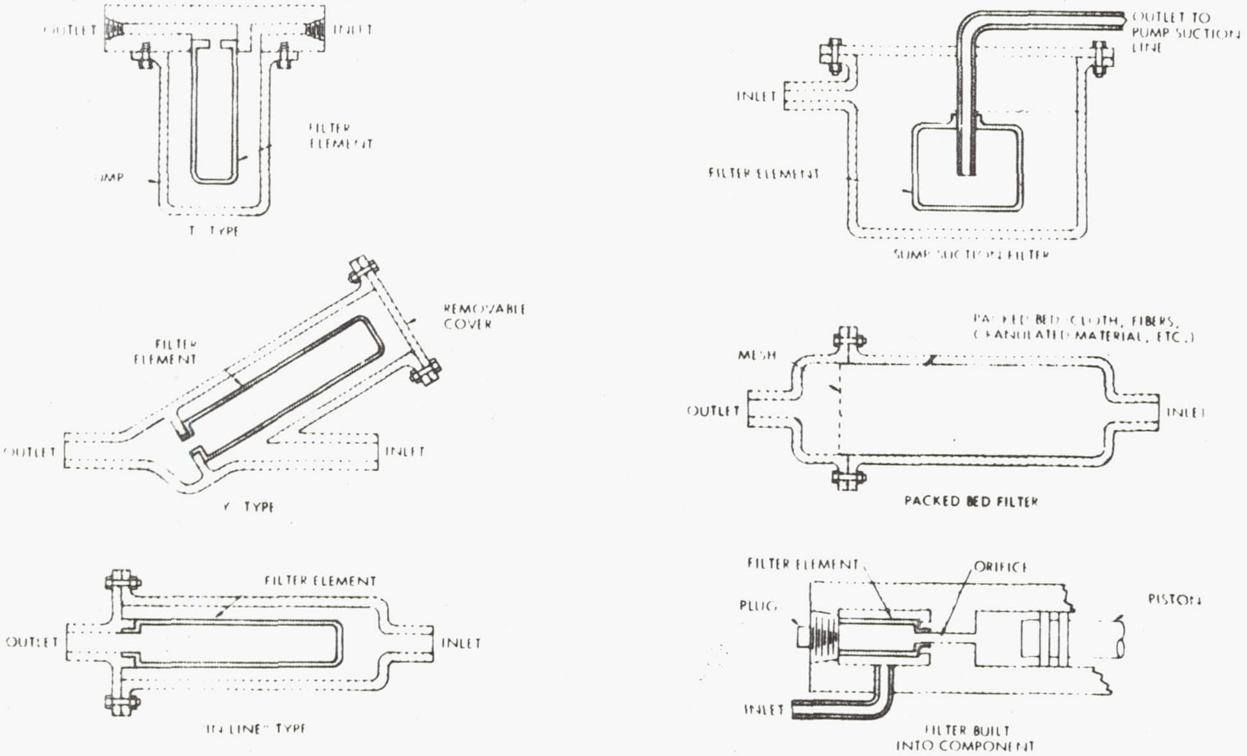


Figure 12 Filter Case Configurations

element replacement, the filter should be designed with sufficient margin between the △P indication and element collapse or failure. This margin should be sufficient to allow one full operation of the system after the △P indication. Stringent inspection controls are necessary if sole responsibility for performance is placed upon the indicator, rather than a periodic scheduled replacement of the filter element.

3) Bypass loops that route the system fluid around the filter if it should become clogged to a specified degree are available from most manufacturers. This feature essentially removes filtration capability from the system, and should be used only in connection with components of such criticality that function must be maintained. The theory is that short-term operation with dirty fluid is better than no operation due to fluid starvation, or collapse of the filter element.

When incorporating a filter into a system, the designer must assure that the element structure and methods of attachment to the case are adequate to withstand the most severe anticipated conditions of pressure, surges, two-phase flow, etc. Migrating portions of filter media have often been the cause of severe mechanical damage to downstream components. Consideration may be given to procurement of components with built-in filtration capability, or to small filters that are adaptable to plumbing fittings such as unions and adapters. Caution should be exercised when using small filter elements. Because of their size limitations, the filter area is very small. If the component sees large quantities of fluid or excessive levels of contamination, the filters will load up quickly and will collapse and migrate downstream. Another problem associated with component filters and fitting screens is that they are seldom maintained or cleaned.

Accessibility for element changeout must be considered from the maintenance viewpoint; space limitations may even dictate case design. In-line filters installed in hard pipe installations present a problem when maintaining the filter or replacing elements. Again, when writing filter specifications, it is recommended that vendor cooperation be invited, and that careful acceptance test requirements be included. The simplest possible case designs are to be recommended for ease of cleaning.

CONSIDERATIONS IN DESIGN

After functional design parameters and material compatibility, probably the most important design consideration for fluid components and systems is contamination control. It is within the designer's province to determine and correct the factors that lead to contamination problems. A few of the items to be considered include materials, finishes, manufacturing processes, clearances, and other physical features. Some specific recommendations are presented in the following paragraphs.

Components

Although component design is a critical factor with respect to contamination control, the system designer must exhibit awareness if he is to make intelligent component selections to meet the required system parameters. When evaluating components to meet system specifications, the following design practices should receive particular attention:

1) Design components so that they will accept large amounts of contamination and still meet their performance requirements;
2) Maintain large flow areas through components, particularly through poppet valves and main sealing surfaces, to reduce fluid velocities and subsequent erosion;
3) Orifice diameters should be held to approximately 800 microns (0.030 in.) minimum. Holes or passages of this size, when used with adequate filtration equipment, should not present any real problem due to particulate matter;
4) If functional requirements demand orifices smaller than 0.030 inch, then consideration should be given to the use of two or more orifices in series, or flow limiting devices such as "visco-jets," to achieve the required pressure or flow as a step-function;
5) Orifice diameters should be no less than one-half the largest particle diameter expected in the system. A more conservative approach would require orifice diameters larger than the largest particle diameter expected in the system;

6) Orifices should be constructed from hard metals because materials such as aluminum will erode on the inlet edge and particles will gouge out the inside diameter, changing the flow characteristics of the orifice and generating metal particles downstream;

7) Clearances should be maintained as wide as possible, with very close scrutiny given to any requirement for less than 0.005 inch (127 microns). Provision of loose clearances not only decreases the sensitivity of the part to contamination, but decreases its capability as a generator, thus favorably affecting further downstream components;

8) Where tight clearances must be provided (0.001 inch or less), consideration should be given to providing a slight taper on the part that widens in the downstream direction; this has been found to be beneficial in alleviation of stiction and silting problems;

9) Where clearances of less than 0.001 inch are necessary, close attention must be paid to cleanliness levels, and filtration equipment type and location;

10) Specify fine surface finishes on parts that must slide against each other. A finish of 8-16 micro inches is recommended. Finishes better than this will not retain oil which is necessary for lubrication;

11) All of the forces (both fluid and mechanical) on moving parts should be balanced to minimize friction and wear;

12) Design valve actions with quick-opening areas to prevent instability, throttling, and high seat velocities. (This is not applicable to gaseous oxygen systems due to heat-of-compression effects.);

13) Direct the flow stream away from critical sliding surfaces. Particles will impinge into the clearance between mating parts and will cause galling or wear;

14) Avoid direct impingement of the flow stream on metallic diaphragms and bellows. Particles in the flow stream will erode the surface;

15) Mechanical or electrical actuating forces applied to sliding mechanisms should be made as strong as possible within reasonable limitations. Any force that is marginal with respect to functional requirements will be susceptible to stiction or silting problems. Since the fine particulate that brings about silting conditions is not easily dealt with by individual filtration, the provision of adequate positioning forces in tight-clearance applications becomes of prime importance;

16) Design internal component filters with ample screen area. The screen must be firmly attached with backup support to prevent breakaway, rupture, or collapse of the filter screen;

17) Those surfaces of components that will be in contact with the operational fluid should be free from crevices, blind holes and threads which all tend to act as dirt traps. They are difficult to clean, and the collected contamination will continually be released as pressures and flows fluctuate;

18) Cylinders, with rods exposed to the environment, should include environmental "boots" to protect against rod corrosion and subsequent rod seal failures;

19) Avoid plating of springs or other parts subject to torsional stress in order to avoid flaking of the coating;

20) Use resilient elastomers for seat materials. Resilient materials will deflect particles and will not erode as will metal seats. Soft seats will compensate for scratches and imbedded particles;

21) Restrain seals on three sides to prevent cold flow, which will decrease clearances on sliding parts. Decreased clearances result in wear and generated contamination;

22) Particular attention should be applied to O-ring groove design. Nibbled O-rings, because of wear, rollings, spiraling, or pressure pulsations, become contaminant;

23) Eliminate sharp edges and threads on leading edges to eliminate O-ring damage upon assembly. Chips of O-rings become generated contaminant to downstream components;

24) Ensure that O-rings do not contain lamination defects or inclusions that will result in nibbled O-rings with subsequent downstream contamination;

25) Place gaskets and seals so as to present a minimum contact area to the working fluid;

26) Chlorinated solvents (cleaning fluids) trapped in the voids of a component may cause stress corrosion;

27) Minimize the use of lubricants in pneumatic components. Particles readily adhere to lubricant films and result in an abrasive mixture;

28) Use lubricants sparingly in pneumatic systems. Many lubricants, particularly those with a teflon base, dry out and become dry particle contaminants;

29) Eliminate feather edges, sharp corners, and other delicate features that are susceptible to fatigue from flow oscillations or failure upon assembly;

30) Design flow paths with gradual enlargements and contractions. Sudden changes in the area will act as particle traps;

31) Disassembly and reassembly capability is necessary for ease of cleaning;

32) Screw-type fasteners or other particle-generating connectors and devices should be minimized;

33) Design with flow-through flushing capability in mind;

34) Flow-through Bourdon tubes can be obtained for pressure gages where trapped cleaning agents may promote corrosion; these have a removable plug in the free end;

35) Eliminate blind holes which become contaminant traps;

36) Avoid the use of bellows of convoluted sections which are difficult to clean;

37) Sand cast holes and surfaces should be avoided, as should any other surface structure that will generate particles;

38) Convoluted hoses are difficult to clean initially and will trap particles, generating large quantities of contaminant during operation.

Manufacturing Processes

Attention to small details during the manufacture of components can reduce built-in contamination from this primary source. Some common recommendations to consider during manufacture are:

1) Carefully deburr each detail part;
2) Clean each detail part with ultrasonics or vapor degreasing to remove cutting oils, lapping compounds, mold release residues, dyes, and other such products;
3) Prohibit the use of glass balls as a grinding or lapping compound. They are difficult to remove from the component, and are particularly detrimental to close fitting parts;
4) Physically locate all clean rooms and controlled environmental areas away from the manufacturing operations;
5) Brazing processes will generate small 20-micron particles;
6) Heat-treat, weld, or braze prior to final machining operations in order to avoid oxide formation;
7) Avoid sand castings. Core molding materials are difficult to remove, and the small inclusions in the casting cannot be cleaned efficiently;
8) Utilize plastic bagging during manufacture, but avoid the use of preservatives and coatings such as Cosmolene;
9) If at all possible, avoid the necessity for cleaning of the finished article by an outside agency, primarily because this means additional disassembly/reassembly/test operations with attendant contamination potential. Component integrity may be degraded because of reassembly by personnel unfamiliar with the function of the article, unequipped with necessary tooling, and unresponsive to immediate control by the design activity;
10) Avoid joining techniques that preclude cleaning of the detailed part or assembly after the previous manufacturing process;
11) Prohibit the use of patching materials on filter elements;

12) When using ultrasonic cleaning, analyze the energy levels being used to prevent deterioration of the product being cleaned;

13) After final cleaning, parts or components should be packaged in heat-sealed double plastic bags, to ensure cleanliness of parts. Redundancy in plastic bags is required should the bag become punctured during handling;

14) When chemical cleaning is required, clean each part at its lowest detail level. Cleanliness cannot always be accomplished at the system level without first cleaning the detail parts.

Materials

Proper choice of materials must be made with respect to contamination susceptibility, as well as functional capability, and is closely related to acceptable manufacturing processes. Such an abundance of materials exist, both metallic and nonmetallic, that an intelligent choice may require the assistance of a specialist in the field, especially on products for which little past experience exists within the design activity. One of the most important aspects, as discussed earlier, involves compatibility not only with the operational fluid, but with anticipated cleaning agents. Certain other aspects that should receive consideration follow:

1) General use of stainless steel is recommended in parts that will be subjected to long periods of idleness or that may be susceptible to internal moisture condensation during shelf storage;

2) Soft or stringy packings should not be used for valve stem seals, etc, as these materials will be gradually deposited in the fluid stream;

3) Choose dissimilar metals for wear points to avoid galling problems and specify adequate hardness levels to minimize the amount of generated contamination;

4) When using dissimilar metals, be aware of galvanic corrosion potential as some fluids and cleaning agents tent to accelerate galvanic corrosion;

5) Aluminum castings tend to shed large quantities of particles in the 3-micron range. In general, aluminum surfaces that will be in contact with the operational fluid should be anodized;

6) Cadmium, zinc, and tin plating tend to flake or scrape easily. Hard chromium plating is susceptible to fatigue when applied to parts that may undergo slight deformations during service;

7) Rubber hoses should be avoided as they are difficult to clean initially, often contain molding residues, and tend to continually shed small particles during flexure. Teflon is a more desirable material, reinforced with stainless steel braid if necessary;

8) Avoid the use of ceramic materials, particularly those with unglazed surfaces. Such surfaces can shed small, very hard particles that can result in abrasive damage;

9) Components that are known to be contamination generators, such as hydraulic pumps, should be subjected to a run-in or break-in period of operation prior to shipment. This technique is very beneficial in that much of the initial generation of wear and abrasion products will take place on, and be removed by, a test stand rather than occur later when the complete system is first placed in operation. The component should be cleaned or flushed after this operation.

Systems Design

The role of the systems designer with respect to contamination control must be centered primarily on the ability to maintain a given cleanliness level by giving proper consideration to the location of components, circuit configurations, assembly methods, types of joints and fittings, and analysis of system contamination sources. Some of the more important practices covering these concepts are:

1) Make provisions for system blow-through, purge, or recirculation capability. It is difficult to ensure a degree of cleanliness in a system containing numerous dead-ended legs. These can probably never be eliminated completely, but the primary flow path should be provided with return capability. Also, provisions can often be made for bypass loops or temporary jumpers to be used only during maintenance activities;

2) Recommended filtration for hydraulic systems should include a course (25 to 150 microns) sump inlet supply filter, 15-micron filters prior to pumps that have close clearances, and 15-micron filters after the pump. If the distance from the pump to the system components is long or complex, additional filtration (15 microns) is required prior to the system components. Critical components in the system may require additional filtration. The fluid added to the reservoir should be filtered to 3 microns;

3) In recirculating systems, use return-line filtration. Large capacity, low micron-rated filters can usually be used since pressures are low and pressure drop is not critical. Such filters prevent generated contaminants from being recirculated through the systems, thus alleviating wear and abrasion problems;

4) Pneumatic systems should be filtered (10 to 25 microns) prior to the storage tank, downstream of the storage tank, and prior to the system components. Additional filtration may be required for critical components, vehicle interfaces, downstream of compressors, or at strategic points in the system if the system is large or complex;

5) Provide accessible drains at the low points of a liquid system to facilitate removal of contaminated fluid and improve flushing capability;

6) Streamline the plumbing runs as much as possible and try to avoid the use of adapters and reducers. Unnecessary bends, loops, and other discontinuities in the plumbing tend to trap particles or increase settling tendencies;

7) Avoid the use of pipe threads and thread lubricants. Teflon tape with the wrap starting 2 to 3 threads from the end has been found to be very satisfactory;

8) Minimize vibration and shock, particularly around filters. Energy introduced into a system materially increases the migration of particles from all types of contaminant traps, and is often purposely used during cleaning operations to enhance the process;

9) Adequate filtration is the best means of maintaining system cleanliness;

10) Reduced flow rates should be employed during the initial start-up of a system to prevent erosion and contamination failures. After initial assembly and during the initial run-in, the system will generally be at its highest contamination level;

11) Hydraulic systems should be designed with closed reservoirs. Atmospheric moisture may cause condensation and attendent corrosion problems, contribute to fluid degradation, or simply impair the purity of the working fluid. Viable organisms will grow in hydraulic oil that contains only a small amount of water;

12) When assigning cleanliness levels, cost effectiveness should be optimized. Cleanliness levels for the entire system need not be as stringent as that required for the end point of the system if filtration is used;

13) Hoses and disconnects will generate large quantities of contaminant. Use filtration downstream of these components;

14) Maintain positive pressure on the system at all times to preclude contamination from the atmosphere;

15) Keep hydraulic components and seals in a "wet" condition to keep the elastomers from drying out;

16) Design a system with consideration to atmospheric conditions such as launch-stand water deluge, sandblasting, salt, humidity, wind, and wash down of components with high pressure water hoses;

17) Never back-flush a filter during system operation as the contaminant collected on the inlet of the filter will be distributed to the system as one gross slug of contaminant;

18) Eliminate air from liquid systems. Pockets of air included in, or in front of, a liquid head will produce very high velocities across valve seats with possible erosion of the seats;

19) If a gas is used to purge, sample, or to perform a functional check of a system designed for liquid service, maintain low flow velocities;

20) When chemically cleaning large pipe distribution systems, use spool pieces in place of the components. Install clean components after the system piping is cleaned;

21) Cylinders and other reservoirs are substantial contaminant traps. Provisions for draining and flushing of such items are necessary;

22) Purge or maintain a positive pressure within electrical enclosures to prevent corrosion due to atmospheric moisture and salt laden air;

23) Protect critical components by filters immediately upstream of the component, or as an integral part of the component. The amount of contamination in the system will determine the filter size and thus the location and type of filter.

Maintenance Considerations

The age-old plea to design with maintenance in mind becomes even more pertinent when contamination control must play an important role in the successful operation of a system. Specific maintenance provisions and schedules must be established if a particular cleanliness level is to be maintained. It is generally recommended that the system must never be entered into for any purpose except for replacement of a failed component. Equipment and ports necessary for any other purpose must be specifically provided. The following are some of the more important functions that should receive careful consideration:

1) System sampling is necessary in order to determine the cleanliness level of an operating system and to establish controls necessary to maintain cleanliness;

2) The number, location, and type of sampling ports must be carefully determined, with particular emphasis on accessibility and convenience;

3) A training program is recommended to make technicians aware of the importance and requirements of cleanliness control;

4) Sample reliability is susceptible to many variables even under optimum physical conditions in the field. Sample analysis by a manual count with microscopic techniques cannot be considered to be better than ±30% accurate between different personnel;

5) Provide sufficient space for ease of filter element changeout. Use dual element filtration equipment where especially critical components are of concern, thus avoiding system exposure to ambient conditions;

6) Establish realistic schedules for filter maintenance. Initially, schedules should be based upon an analysis of the cleanliness level specifications. Schedules may then be adjusted after the system is in operation and operating experience is gained on the amount of actual filter loading. Schedules should include a margin of safety;

7) Specify depth-type filters where possible to reduce maintenance requirements. Consider the use of filter bypass loops to facilitate service and testing operations;

8) Do not perform any field disassembly of cleaned components. These should be bagged and sealed immediately upon removal from the system plumbing, and transported to a clean environmental area for analysis;

9) When very clean conditions are required, or when environmental conditions are poor, a portable plastic tent with low internal positive pressure capability is recommended to help preserve system integrity when component removal must be performed. Safety considerations require that air be the pressurant;

10) Component ports and open plumbing ports should be immediately capped or plugged. The use of plastic caps is not advised, since they tend to shed particles upon being installed;

11) The use of lubricants should be carefully controlled. Only the first three threads of a fitting should be lubricated. Teflon tape is recommended instead of lubricants;

12) When known contamination generators are replaced because of wear and subsequent deterioration of performance, further attention must be given to the entire system since the contamination that has been generated has undoubtedly been distributed far downstream. Thorough system fluid analysis should be performed, and adequate system flushing, and subsequent filter element replacement must be accomplished to return the complete system to an acceptable cleanliness level. Only clean, bagged, and sealed components should be reassembled into the system;

13) A bubble-point check should be performed on filter elements to ensure filtration effectiveness of the element. This check should be made after the element is manufactured and following any cleaning operations;

14) Identical or similar components should be cleaned at one time to amortize the setup costs for cleaning. Setup costs are the same for one component or for several components;

15) Open fittings should be cleaned with a suitable solvent immediately prior to assembly;

16) Specific procedures should be implemented for sample taking, test equipment hookup, and make-up fluid addition;

17) Maintenance operations should be prohibited insofar as possible during rainy or windy weather, or while dirt-producing operations are being performed nearby;

18) The first replacement of filter elements should occur just after initial run-in of the system, since the major contaminant accumulation will occur during this period.

OPERATIONAL PRACTICES

Consideration for contamination control must not stop with the design and installation phases of a fluid system. The third aspect that must not be neglected is the manner in which the system is operated. Unless knowledgeable and attentive procedures are followed, any clean system will very quickly fall out of specification. Operating procedures should be prepared by the design activity and contain the following requirements as a minimum.

Initial System Operation

The first service that a fluid system normally sees after installation is a validation operation to prove satisfactory performance, usually involving the use of test equipment. Controls should be specified in several areas:

1) Equipment required to fill liquid system reservoirs should be cleaned at least to the system level and the fluid should pass through a fine filter before entering the reservoir. Merely dumping fluid from an open container, or using any available barrel pump, will almost certainly contaminate the fluid before it even reaches the system;
2) Any test equipment that is to be attached to the system, and any fluid contained therein, must be cleaned at least to the system level. This is an area often overlooked on ground support equipment used on site;
3) Since the fastest accumulation of contaminants in recirculating circuits occurs during the initial run-in period, when much leftover dirt from assembly and products of wear and abrasion will be flushed out, the first replacement of filter elements should be performed at an earlier time than planned for routine maintenance;
4) If initial system cleanliness has been necessarily haphazard because of the physical configuration of the circuit, consideration should be given to the use of provisional filters until the desired contamination level is obtained. The temporary filtration equipment can then be removed, and reliance placed on the system filters.

Normal System Operation

Some effective ways to control contamination are:

1) One of the most effective ways to prevent entrance of airborne contaminants into an operational fluid system is to maintain continuous, positive pressure on all plumbing (blanket pressure) during periods of inactivity. This is often easy to accomplish in gaseous systems, and can be done without undue complications in hydraulic systems. It is not desirable to retain certain types of liquids such as cryogenics or propellants that are likely to be corrosive or produce a safety hazard due to boiling, in the system piping. Such systems should be drained and blanketed with an inert gas such as nitrogen. This method is particularly effective in preventing internal condensation resulting from the entrance of atmospheric moisture, which is often an insidious mode of performance degradation;

2) Nearly all fluid systems contain some electrically-operated components, such as solenoid valves. The effect of atmospheric contamination on the electrical portion of such components is often overlooked by the fluids designer. Inert gas purging of electrical connectors is another important item to consider especially when operating in an atmosphere that is moist or salt-laden. Potting should be considered, but may not always be adequate. Cases have been noted where contacts have been inadequately cleaned, or where moisture has been trapped inside the potting compound, and corrosion has proceeded internally;

3) Hydraulic systems should be constantly filled with fluid to keep the various component seals wet during long periods of system inactivity. Seals of a configuration or material selected specifically for operation in a liquid environment may shrink or distort if allowed to dry out, thus posing a potential leakage problem;

4) Guard against overheating of hydraulic fluid -- the temperature limitations contained in the fluid procurement specifications should be carefully observed. Overheated fluid may chemically decompose, creating large amounts of sediment, or resulting in the deposition of gums or varnish throughout the system.

SAMPLING TECHNIQUES

The stipulation of a required level of cleanliness for a fluid system inherently dictates that samples of the operational fluid be collected and analyzed for contamination. The basic steps of particulate analysis for a typical application consist of:

1) Obtaining a truly representative sample of the fluid;
2) Separating the particulate matter from the sample;
3) Determining the quantity of particulate that falls within several arbitrary size ranges.

Several different methods are commonly used to accomplish these tasks, none of which is completely satisfactory in all respects. The ASTM and SAE have published several different procedures that deal with this subject. Although sampling operations are not usually controllable by the design activity, a discussion of several aspects of the subject is presented below to make the designer aware of operations that reflect, or may affect his system requirements. (See References 4, 5, 9, and 10 for further details.)

Visual Examination

Samples of liquids may be collected in bottles and examined with the naked eye or under a microscope for proper color, evidence of sludge or suspended material, or other gross evidence of contamination. Gases may be passed through a Millipore (or equivalent) filter disc which is originally pure white; any contamination in the gas will cause discoloration of the filter which is then compared to a standard set of discs that can be obtained for the purpose. Approximation of a certain shade of discoloration is equivalent to a known contamination level. Obviously, these methods are sensitive to technique and the technician's capability, and can be used only when loose requirements exist.

Open Bottle Method

A common method of obtaining samples in hydraulic and other nontoxic liquid systems is the opening of a convenient drain valve at some point in the system and catching a sample of the fluid in an open glass container. The sample is then usually taken to a laboratory where it is strained through a Millipore (or equivalent) filter disc, usually of 0.80 micron absolute rating with a printed grid. Different color discs are available to provide contrast, depending on the type of contaminant that is present. The disc is then placed in a microscope and, with the aid of a calibrated eyepiece, the number of particles within a given size range is counted manually. Typical size ranges are 5-15 μ, 15-25 μ, 25-50 μ, 50-100 μ, 100-150 μ, and 150+. The number of particles smaller than 5 μ is usually quite large and for that reason not counted. If the fluid is particularly dirty, it is common practice to count the particles in one grid square and multiply by the number of squares. The size range used will depend on the specification to which the fluid is being checked. The final count must be related to the volume of the sample, often 100 mℓ. This method is subject to a number of possibilities for error, some of which are enumerated along with recommendations in each case:

1) Whether a sample typifies the fluid from which it is drawn depends upon the manner in which the sample is taken. First, the system should be flowing at the nominal design flow rate, otherwise settling of the fluid may result in an unrealistic concentration of contaminants. Many maintain that to be truly representative, a device similar to a pitot tube should be inserted in the plumbing to draw fluid from various points across the pipe diameter; this is known as isokinetic sampling. Tests comparing the results of the two methods, indicate that the need for this refinement is somewhat debatable in liquid systems;

2) The sampling valve itself may be dirty; any contamination contained thereon may be washed into the sample. To help avoid this problem, the valve port should be carefully washed with clean solvent before the sample is drawn. Also, a quantity of fluid should be flushed through the valve before the sample is collected; this not only increases the validity of the fluid, but helps wash away particles that may be generated by the physical operation of opening the valve;

3) The collection bottle itself may be contaminated to a higher degree than the fluid. Extreme care must be taken in handling the bottles in the field. They must be thoroughly cleaned prior to use. A background count cannot be established for a bottle. Cleaned closures should be provided and put in place immediately to preclude entrance of atmospheric contaminants;

4) Since the entrance of extraneous contamination can never be completely eliminated, it is advisable to collect as large a sample as is practicable, such as 1000 mℓ (1 liter). The larger the amount of actual fluid particulate, the smaller will be the percentage of particulate that is extraneous (background). Thus, the sample will be more realistic. Particle counts can later be related to a standard volume such as 100 mℓ if required by specification. If relatively dirty systems (i.e., Level 8 of NAS-1638) are being sampled, a 100-mℓ sample is recommended since a 1000-mℓ sample will contain too many particles and cannot be counted by microscopic techniques.

Field Monitors (Bomb Samplers)

Several of the major filter manufacturers supply kits that contain all of the hardware necessary for obtaining fluid samples from pressurized systems under conditions considerably more precise than those associated with the open bottle method. Such kits consist basically of a quick-disconnect coupling, a three-way valve, a graduated flask, a membrane filter and holder, and interconnecting tubing. The filter holders are disposable. Membrane discs are assembled into the holders by the manufacturer under ultraclean conditions. In practice, the system fluid is routed from the quick disconnect coupling to the membrane holder and into the flask. The 3-way valve allows the fluid to first flush the connections and tubing into a waste container, then be directed across the filter membrane and into the flask. The 3-way valve is then closed and the apparatus disconnected intact from the system, and transported to a laboratory for analysis. For particulate counting only, the disposable filter and holder are utilized. However, the fluid collected in the flask is available for further analysis such as nonvolatile residue, trace impurities, moisture content, etc. These kits are equally applicable to liquid or gas sampling. When sampling gases, a known flowrate must be established, thereby permitting collection of a sample of known volume. This may be accomplished by flowmeters, or by a timed amount of flow through a calibrated orifice.

Bomb sampling equipment exhibits a distinct superiority over the open bottle method in that extraneous contamination is minimized, if care is exercised in the operation. The question of sample representation is, however, still present. Consideration of isokinetic techniques should still be given to gaseous systems.

Millipore discs are limited by the amount of differential pressure they will accept without rupturing. High pressure membranes constructed from teflon or nylon mat will accept 1500 psi differential pressure. Millipore discs are available in white and different colors, and provide background contrast in order to make the job of counting particulate easier.

Automated Sampling

Equipment is presently available from several manufacturers for automatic, continuous on-line particulate sampling. These counters operate on one of several different principles involving optics or electronics. They are accurate, sensitive, and require no physical handling or manual counting methods. On the other hand, they are difficult to adapt to rugged field conditions, being essentially laboratory type equipment. Remote sensors may be located in the system, with the recording device located in a controlled area. Automatic counters sense particulate size on a projected area or volume basis. Since nearly all particulate specifications are presented in terms of the longest particle dimension, a direct correlation cannot be made with automatic counters because of the different standard used. A distinct disadvantage of automatic counters is that they interpret air bubbles as particles and readily present them as a high particulate count. Such equipment is not in wide use in field installations at the present time, but every possible consideration should be given to its use.

Knowledge possessed by the designer of basic sampling procedures as outlined above should enable intelligent provision of sampling hardware and inclusion of meaningful requirements in the system operating procedure. This knowledge should also convince the designer that sampling is an imperfect art and should not be relied on as a perfect indicator of the contamination level within a fluid system.

FLUIDS

The following discussion is intended to acquaint the designer with the degrees of particulate contamination that may be expected in common procurement specifications for nitrogen, helium, and hydraulic fluid.

Nitrogen

MIL-P-27401B dated 19 September 1962 (current issue) is the usual specification referenced for the procurement of nitrogen for ground systems use. This document covers both gaseous and liquid types, and specifies that either form shall contain not less than 99.5% by volume nitrogen, and not more than 26.3 ppm moisture at standard conditions. No particulate size or weight limitations are placed on the gaseous form, but in the liquid, solid particulate shall not exceed 1.0 mg/liter, as trapped by a 10μ absolute membrane filter. Essentially this means that there is no quantitative limitation on particulate matter smaller than 10 microns, and that there is no size limitation on the 1.0 mg allowable mass quantity. It is specified that a 40-micron absolute filter shall be installed between the manufacturer's plant system and the container to be used for delivery of the liquid nitrogen. From these requirements, the designer should expect:

1) An appreciable quantity of particles less than 10μ that may be detrimental due to silting and stiction;
2) A likelihood of fibers up to 400μ (that could pass the 40-micron filter);
3) A determinable quantity of particles 10μ to 40μ (up to an aggregate mass of 1.0 mg);
4) No restrictions are placed upon the cleanliness level of the delivery container and its initial particulate contaminants may be transferred out of the container with the fluid.

Helium

MIL-P-27407 Amendment 1 dated 8 January 1965 (current issue) is the usual specification referenced for the procurement of gaseous helium. This document specifies that the helium gas shall contain not less than 99.995% by volume helium, and not more than 9.0 ppm moisture at standard conditions. There are no particulate size or weight limitations specified in this specification, and no filtration is specified between the manufacturer's plant and the delivery container. Extraneous particulate from the delivery container may again be anticipated.

Hydraulic Fluid

1) MIL-H-5606B dated 26 June 1963 (current issue) has for years been the common specification referenced for the procurement of hydraulic oil for general use. Temperature limitations are -65 to +160°F in open systems and -65 to +275°F in closed (airless) systems. Moisture is limited to 100 ppm at standard conditions. Solid particulate is limited to 0.3 mg/100 milliliters with size restrictions as follows for the same volume:

Size Range (microns)	Allowable Number
5-15	2500
16-25	1000
26-50	250
51-100	25
Over 100	None*

*None is defined as one less than the number of samples taken during a given analysis.

Permission is given in this specification for the addition (up to 20%) of polymeric viscosity-temperature coefficient improvers. Recently, industry literature has reported that methacrylates added for this purpose greatly increase the tendency of submicronic particles in the fluid to agglomerate into larger particles during periods of storage. Thus, oil that met specification when it left the manufacturer may evidence sludge in the can when opened later for actual use. These agglomerates may be broken up by severe agitation, but will reform if left in a static condition. A vibratory environment appears to increase the rate of agglomeration, apparently by increasing the force with which particles strike each other. The methacrylate apparently serves as an adhesive. Typical agglomerate size may often reach several hundred microns;

2) MIL-H-6083C Amendment 1 dated 11 September 1967 (current issue) is a more recent procurement specification for hydraulic oil with preservative properties. This oil was primarily intended as a preservative and testing medium, but is commonly used in many hydraulic systems because of the corrosion inhibitor additive. No specific temperature limitations are given in the specifications, but implied limits are -65 to +160°F in open systems and -65°F to +275°F in closed (airless) systems. Moisture is limited to 500 ppm at standard conditions. No mass limitation is given on solid particulate matter, but the following size limitations are imposed per 100 ml volume:

Size Range	Allowable Number
5-15μ	2500
16-25μ	1000
26-50μ	250
51-100μ	25
Over 100μ	5

The same allowable 20% addition of acrylic polymeric additives is allowed for viscosity improvement, and in addition additives are allowed for corrosion inhibition. Apparently due to this difference, the literature reports that this type of oil is much less subject to agglomeration than is MIL-H-5606. No problems result when the two types of oil are mixed together in any proportion. Serious consideration should be given to this oil, primarily because of its improved performance with respect to corrosion.

CLEANLINESS STANDARDS

As a matter of education for the designer who is unfamiliar with the efforts of various technical societies along the lines of contamination control, tabular size/quantity information is presented in this section for three different standards that have been proposed at various times, and that have been widely used and quoted in the literature. All of these specifications are directed toward hydraulic fluid and components. To the author's knowledge, no similar documents have been formulated for gaseous commodities of any type, or for any other specific liquids. It should be emphasized that manual counting of particles is not an exact science. Particle counts can vary ±30% between skilled technicians using the same equipment. The variance is often larger than this. Analysis of particle count spectra should be viewed in a broad sense, rather than as concise numbers in explicit size ranges.

Cleanliness Specification -(NAS 1638)

Although this specification presents both size and mass criteria for particulate matter as separate recommendations, no correlation is intended between the two. The recommendations are for hydraulic fluid effluent from parts, assemblies, lines, and fittings. The cleanliness levels are based upon a 100-ml fluid volume. No recommendations are given for application of a specific level of class to a particular piece of hardware. The document was prepared in 1964 by the Aerospace Industries Association of America, Inc., and coordinated with SAE Committee A-6.

1) Particulate Size Limitations

*Particle Size Range (microns)						
Class	0-5	5-15	15-25	25-50	50-100	Over 100
00	Unlimited	125	22	4	1	0
0		250	44	8	2	0
1		500	89	16	3	1
2		1,000	178	32	6	1
3		2,000	356	63	11	2
4		4,000	712	126	22	4
5		8,000	1,425	253	45	8
6		16,000	2,850	506	90	16
7		32,000	5,700	1,012	180	32
8		64,000	11,400	2,025	360	64
9		128,000	22,800	4,050	720	128
10		256,000	45,600	8,100	1,440	256
11		512,000	91,200	16,200	2,880	512
12		1,024,000	182,400	32,400	5,760	1,024

*No limitations are placed on size or quantity of fibers.

2) Particulate Mass Limitations

Class	100	101	102	103	104	105	106	107	108
Weight (mg)	0.02	0.05	0.10	0.30	0.50	0.70	1.0	2.0	4.0

Note: Sample volumes larger than 100 ml are recommended for Classes 100, 101 and 102.

Cleanliness Specification - (ARTC-28)

This specification again presents size and weight criteria separately, with no correlation intended between the two. This document is intended to apply to hydraulic fluid as such. The cleanliness levels are based upon a 100-ml fluid volume. Some recommendations are given for specific applications, as noted in the tabulations. The document was originally prepared in 1961 by the AIA, but underwent significant revision in 1964. It is this revised data that is presented below; the earlier data is seldom referenced.

1) Particulate Size Limitations

Particle Size Range (microns)							
Class	0-5	5-10	10-25	25-50	50-100	Over 100	Fibers
1	Unlimited	To be determined	220	20	5	0	2
2			530	60	10	1	3
3			1530	150	15	1	4
4			5530	420	40	3	7
5			1650	320	25	0	1

Note:
1. Class 1 is for ground test units.
2. Class 2 is for servo and power systems.
3. Classes 3 and 4 are for aerospace ground equipment.
4. Class 5 is for refinery supplied fluid.

2) Particulate Mass Limitations

Class	11	12	13	14
Weight (mg)	0.1	0.3	0.5	1.0

Combined Tentative Standard

Between the two editions of ARTC-28, a tentative revision was formulated (largely to make the original size ranges coincident with publications of other societies). This document received wide circulation and is often quoted in the literature. Although never released as a distinct number-bearing document, this table came to be known as the "combined AIA-SAE-ASTM tentative standard." Again, the cleanliness levels are based upon a 100-ml fluid volume. Approximate application information is provided. The intended usage was the same as ARTC-28. No mass limitations were included, nor are any limitations placed on fibers. Further use or references to this data should be avoided; it is included herein as background material only.

	Particle Size Ranges (microns)						
Class	0-2.5	2.5-5.0	5-10	10-25	25-50	50-100	Over 100
0	Unlimited	Pending	2,700	670	93	16	1
1			4,600	1,340	210	28	3
2			9,700	2,680	380	56	5
3			24,000	5,360	780	110	11
4			32,000	10,700	1,510	225	21
5			87,000	21,400	3,130	430	41
6			128,000	42,000	6,500	1,000	92
7-10	← Pending →						

Approximate Application Note:

Class 0 - Rarely attained
Class 1 - MIL-H-5606B
Class 2 - Good missile system
Classes 3 and 4 - Critical system, in general
Class 5 - Poor missile system
Class 6 - Fluid as received
Class 7 - Industrial service

In addition to these three documents which are reasonably well recognized throughout the industry, there are myriad specifications that have been generated over the past several years by individual companies, the military, and NASA; no attempt will be made to include any of these here. Nearly all have evolved over a span of time, based on successful experience; few if any, will be found to correlate exactly with the above so-called industry standards.

CLEANLINESS LEVEL RECOMMENDATIONS

This handbook has attempted to enumerate many of the more important facets of the design, operation, and maintenance of ground fluid systems which must be considered if effective contamination control is to be achieved. This diversity of factors essentially means that any given fluid system should be dealt with on an individual basis when establishing cleanliness levels. Nevertheless, those persons undergoing their initiation into the cleanliness field invariably feel the need for some baseline or ground rule, a "jumping-off place" from which to begin any individualized analysis. For this purpose, cleanliness level recommendations are given in this section. These recommendations follow the philosophy that the most economical means to achieve long term system reliability in terms of contamination sensitivity is to conform to four basic criteria:

1) Design or select all components for maximum dirt tolerance;
2) Include thorough filtration capability in the design;
3) Initially clean components and systems to a readily obtainable, economically feasible level;
4) Follow strict, meaningful operational and maintenance procedures.

The following cleanliness levels are not intended for across-the-board applications to any fluid system, but rather should be considered as a realistic starting point for an individual system analysis. The following specific restrictions apply:

1) Ground systems only, operating under ordinary ambient conditions at pressures up to 6000 psig;
2) Fluids imply hydraulic oil, gaseous nitrogen, and gaseous helium;
3) Hydraulic servo valves or other extremely close-tolerance components are not present in the system;
4) Systems in which one contamination failure will not result in mission abort or failure, or result in a hazard to personnel.

Hydraulic Recommendations

It is expected that components will be cleaned by the rinse method in a controlled environment, and that system fluid samples will be obtained through the use of a "bomb" sampler. Criteria is per 100 ml of fluid. A minimum of 200 ml of solvent per square foot of significant surface area should be used in the rinse sample.

1) Component Cleanliness Level

Particle Size (micron)	0-5	5-15	15-25	25-50	50-100	Over 100
Quantity per ft^2 of Significant Surface Area	No limit	48,000	8,500	1,500	250	50

2) System Cleanliness Level

Particle Size (micron)	0-5	5-15	15-25	25-50	50-100	Over 100
Quantity per 100 ml of Fluid	No limit	64,000	11,400	2,025	360	64

Pneumatic Recommendations

Again, rinse methods for components and bomb sampler systems are recommended. The following recommendations are based on levels that have been found to be acceptable through extensive experience and tests with pneumatic systems. Criteria is per square foot of surface area for components and 100 grams of gas for the system. A minimum of 200 ml of solvent per square foot of significant surface area should be used for the rinse sample, or 200 grams of gas for a system blow-down sample. Membrane rating should be no greater than 0.8 micron absolute.

1) Component Cleanliness Level

Particle Size (micron)	0-300	300-500	500-1000	Over 1000
Quantity per ft^2 of Significant Surface Area	Unlimited*	10	2	None

Fiber Length (micron)	0-750	750-2000	2000-6000	Over 6000
Quantity per ft^2 of Significant Surface Area	Unlimited*	20	2	None

*Total filterable solids limitation 0.25 mg/ft^2

2) System Cleanliness Level

Particle Size (micron)	0-300	300-500	500-1000	Over 1000
Quantity per 100 grams Gas	Unlimited†	10	2	None

Fiber Length (micron)	0-750	750-2000	2000-6000	Over 6000
Quantity per 100 grams Gas	Unlimited†	20	2	None

†Total filterable solids limitation 0.3 mg/100 grams gas

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