IMPROVING COMMERCIAL AIRLINER HYDRAULIC SYSTEM RELIABILITY THROUGH CONTAMINATION CONTROL

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ABSTRACT

Abundant research and field experience has established that fluid contamination degrades the performance and life of machinery. In order to improve component and system reliability and performance, industrial associations and equipment manufacturers are recommending clean fluids and/or fine filtration. A wide variety of industrial equipment currently operates within these recommended levels of fluid cleanliness. Improved fluid cleanliness will similarly provide the benefits of longer MTBF for commercial aviation hydraulic systems. Cleaner fluids can be achieved by modern contamination control methods such as fine filters, and accurately measured using on-line particle counting. This paper reviews the effects of contamination and the status of system cleanliness in machinery, then recommends a target cleanliness level of NAS 1638 Class 3 for commercial airlines, and discusses how this target can be readily achieved.

CONTAMINATION AND RELATED FAILURE MECHANISMS

RELIABILITY - Reliability is the average time a device operates without failure. Reliability affects maintenance costs, manpower allocations, spare parts logistics, and disruptions in service. Furthermore, in complex systems safety is a function of component reliability, design, and duty cycle. Improving component life through contamination control enhances all aspects of reliability.

ABRASIVE WEAR AND FATIGUE WEAR - Several forms of wear produced by contaminants occur at the concentrated contacts between component surfaces, as illustrated in Figure 1. A fluid film forms between the opposing surfaces because of relative motion. The film is maintained because fluid viscosity is an exponential function of pressure; at the high pressures within the contact zone the fluid momentarily becomes highly viscous (a semi-solid). The fluid film acts to distribute the load throughout the entire area of the contact. It also greatly diminishing wear and friction by inhibiting metal-to-metal contact between the opposing surfaces.

Particles smaller than the thickness of the fluid film pass through without damage. Particles equal to or greater than the size of the film cause wear. By making simultaneous contact with both surfaces they focus the load into a small area, resulting in plastic deformation of the component surfaces. In sliding contact, these particles gouge and cut away material; this is abrasive wear. In rolling contact, particles pit and dent the surfaces; this leads to fatigue spalling. Damage is proportional to particle hardness, sharpness, and the number of particles greater than the fluid film thickness.

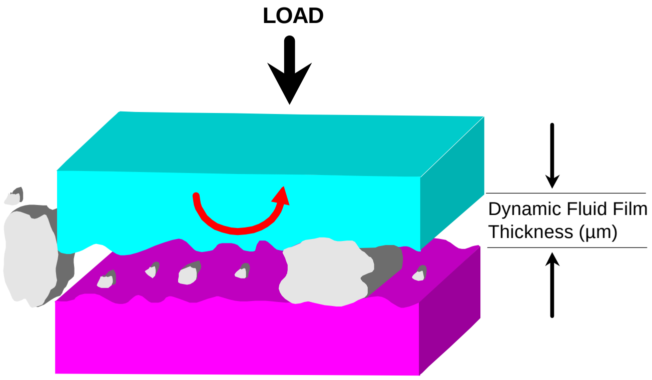

Figure 1. Contamination and Wear

Table 1, extracted from the ASME Wear Control Handbook [1], compiles film thickness for several relevant components. Sliding clearances within hydraulic components range down to 0.5 µm, and down to 0.1 µm for rolling contact bearings. Since particles down to the sizes of these fluid films are harmful, it is useful to know the sizes of contaminant particle sizes in hydraulic systems. Figure 2 shows typical particle size distributions as represented by several Classes of NAS 1638 [2]. Also provided for reference is the size distribution of a 1 mg/L concentration of AC Fine Test Dust (ACFTD). The essential point is that contaminated hydraulic systems contain multitudes of damaging particles equal to or greater than the film thickness of system components.

STICTION AND SILTING - Electrohydraulic and hydromechanical servo actuators use a spool/sleeve to control flow from the valve to the actuator. An example is shown in Figure 3a. In almost all cases, this spool/sleeve mechanism is the most sensitive to contaminant related failures. Two general modes of failure are related to stiction and silting.

Table 1
Dynamic Fluid Film Thickness

Component	Thickness (µm)
Rolling Bearings	0.1 - 1
Gear Pumps	
Tooth to side plate	0.5 - 5
Tooth tip to case	0.5 - 5
Piston Pumps	
Piston to bore	5 - 40
Valve plate to cylinder	0.5 - 5
Actuators	50 - 250
Servovalves	
Flapper wall	18 - 63
Spool to sleeve	1 - 4

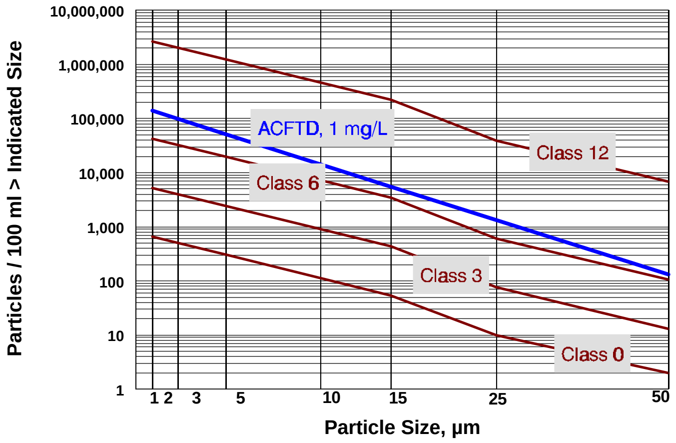

Figure 2. Typical Contamination Levels

Stiction - Stiction occurs when the valve becomes very unbalanced. The side loads cause microscopic adhesion (cold welding) to occur between the metal contact surfaces of the spool and sleeve. Many manufacturers reduce these unbalanced forces by providing annular "balancing" grooves around the spool lands. However, contaminants can get caught in these grooves causing unbalanced spool forces. See Figure 3b. Mild stiction causes an increase in break-out force resulting in jerky valve movement. Severe stiction can cause jamming failures in some valve designs.

Silting - Silting between a spool and sleeve occurs when the valve is stationary and pressurized. Particles larger than the radial clearance are filtered out at an oil port or within the annular spool/sleeve clearance space. Even particles smaller than the clearance can form a "dam" and cause silting. Figure 3c illustrates contaminants obstructing the valve port. As the contaminants collect, they cause unbalancing, an increase in break-out friction and stiction. Response time is increased and the valve can become unstable with a large hysteresis. In severe cases, the valve can become jammed and inoperable, sometimes called contaminant lock. References [3] and [4] provide a more thorough description of silting and contaminant lock.

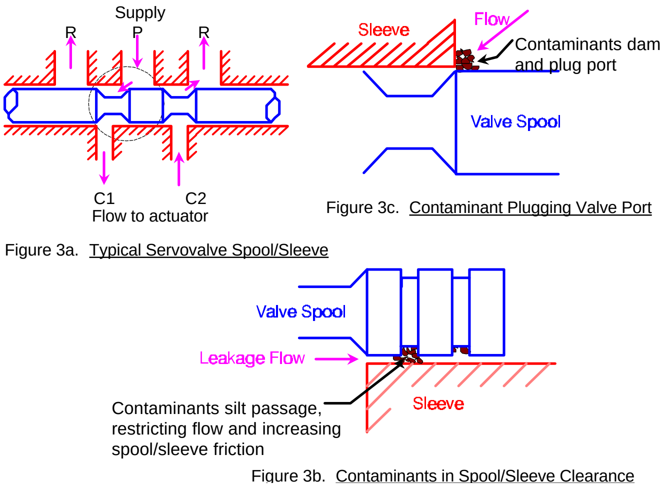

Figure 3a. Typical Servovalve Spool/Sleeve

Figure 3c. Contaminant Plugging Valve Port

Figure 3b. Contaminants in Spool/Sleeve Clearance

Figure 3. Contamination and Servovalves

Another difficulty, somewhat related to silting, is fouling of heat exchange surfaces by particle deposition. An insulating layer forms which leads to higher operating temperatures that exacerbate other wear processes.

EROSION - Erosion is caused by high velocity particles impacting component surfaces. High velocity is created by large pressure drops across small distances, such as found in diesel fuel injectors, jet engine inlet nozzles, servovalve metering edges, and valve plates of piston pumps. As illustrated in Figure 4, a perpendicular angle of attack results in pits and cracks analogous to fatigue. A shallow angle of attack produces abrasive wear similar to sliding contact abrasion [5]. In both cases wear increases with particle hardness, sharpness, mass, velocity, and number.

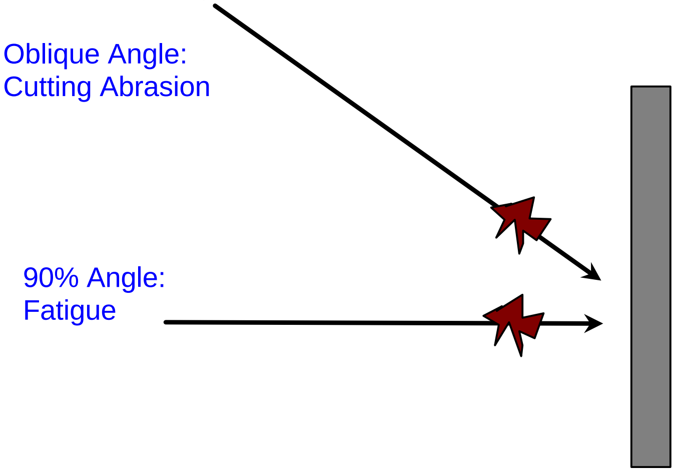

Figure 4. Erosion Wear

The more serious form of erosive wear is the cutting abrasion produced by shallow angles of particle impaction. This is precisely the geometry of particle impaction into critical surfaces such as the edges of a spool or sleeve in a servovalve and the valve plate on a piston pump. Erosion damages the metering edges of the spool or sleeve, reducing the pressure gain, increasing null leakage, and making it more difficult for the valve to function properly. An example of this type of failure is shown in Figure 5.

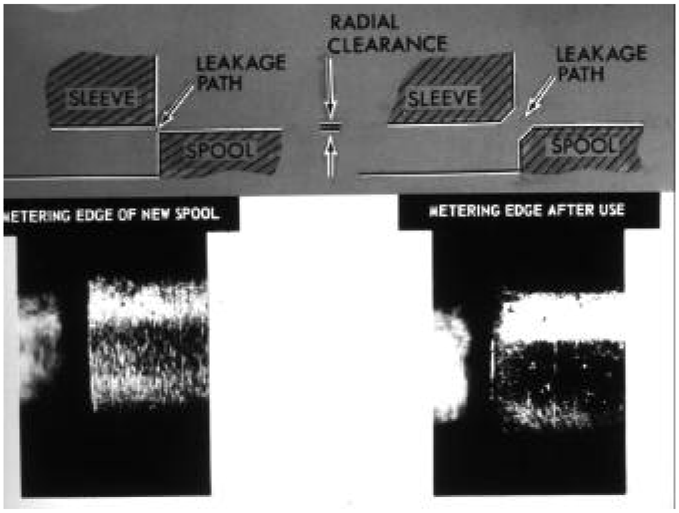

Figure 5. Servovalve Spool Erosion Damage

WATER CONTAMINATION - Water is another fluid contaminant causing component damage. Water occurs in hydraulic fluids in both free and dissolved states. Free water is the most troublesome as it can cause corrosion. Also, free water collected in valves may freeze at low temperatures. This could be particularly troublesome for aircraft operating in cold climates or at elevated altitudes.

Water may severely shorten the life of aerospace phosphate ester hydraulic fluids through the chemical reaction of hydrolysis. Resulting high acid levels force fluid disposal and replacement. Fluid may also be degraded by the process of oxidation. As shown in Figure 6, the combination of water and metal surfaces (such as from wear debris) is the worst case scenario.

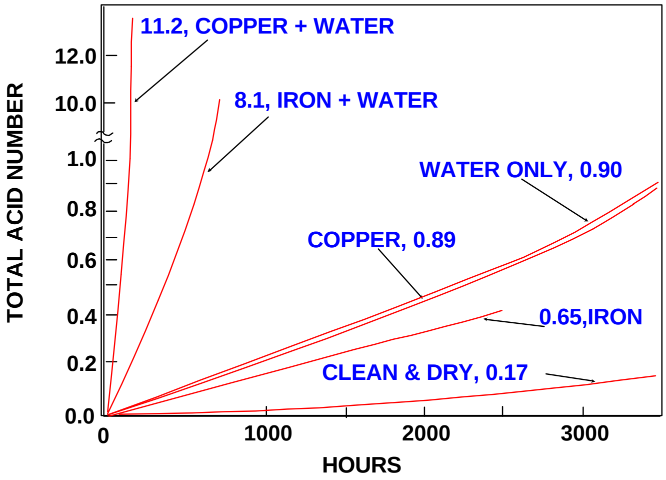

Figure 6. Contamination and Oil Breakdown

Water may also react with fluid additives, precipitating them from hydraulic fluids. These precipitates deplete additives from the fluid and can contribute to component failures as well as premature filter plugging. In addition, dissolved water has been found to diminish rolling bearing fatigue life, as shown in Table 2.

Table 2
Effect of Water on Bearing Fatigue

Lubricant	Water Concentration	Relative Life Factor
SAE 20	25 ppm	4.98
SAE 20	100 ppm	1.92
SAE 20	400 ppm	1.00

SOLVENT CONTAMINATION - Solvent contamination can also be quite destructive in a hydraulic fluid. Chlorinated solvents, when allowed to combine with minute amounts of water, hydrolyze to form hydrochloric acid. Acid attacks internal metallic surfaces in the system, particularly those that are ferrous, and produce severe rust-like corrosion. There have also been cases where a hydraulic system was contaminated with a chlorinated solvent, and within hours the metering edges of the electrohydraulic valves were damaged beyond repair.

CONTAMINATION STUDIES

This section provides highlights from over 20 years of research. For more in-depth reviews of this work, see References [3-20].

Pumps - In 1985 Ohlson presented a study performed by NADC (Naval Air Development Center) in Warminster, Pennsylvania [6]. Wear of aircraft piston pumps was measured for three levels of filters: 15 μm, 5 μm, and “hyperfine”. The first two met the Mil-F-8815 specification. The latter was a developmental filter rated at 0.8 μm by the manufacturer. Parameters for this investigation are summarized in Figure 7. For each test a new pump was:

1) run for 250 hours of testing
2) disassembled for wear measurements then reassembled
3) run for another 250 hours of testing accelerated by the addition of AC Fine Test Dust
4) disassembled for a final set of wear measurements.

The investigators found that the mode of pump wear observed during the test was the same as wear found during flight. The amount of wear detected was always least for the 0.8 μm filter. Figure 7 shows the relative amounts of wear found for the three pumps. The study concluded that by capturing particles the size of the thickness of the fluid film, using finer filtration resulted in less wear and longer pump life.

Servo Actuators and Servovalves - The effects of contamination on servovalves have been studied and discussed by numerous investigators, e.g., References [3-4] and [7-18]. Several different test techniques have been proposed; however, there is no standard industry method for evaluating the sensitivity of a servo. Some of the results of previous studies are presented below to illustrate the effects of contamination on servo performance.

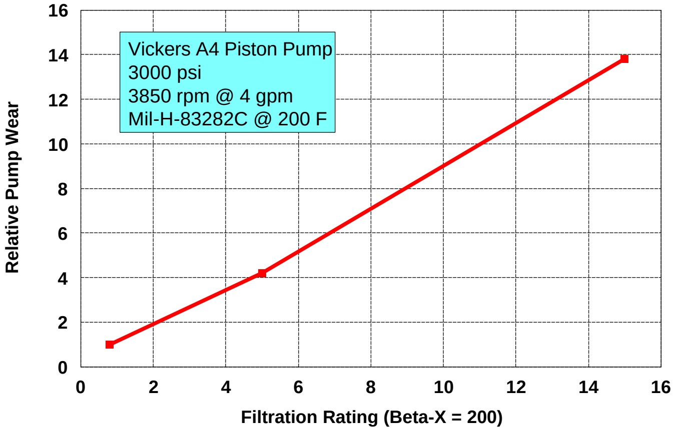

Figure 7. NADC Pump Wear Test

Tessmann and Foord (Oklahoma State University) [11] studied the effects of particle size distribution on servovalve performance. They also found a significant effect of contaminants on hysteresis as shown in Figure 8. The result varied from an increase in hysteresis to complete spool lock. Figure 9, reproduced from the results of their study, with data points plotted at the midpoint of the size range of the contaminant injected, shows that for the particular valve tested, the highest sensitivity was in the 5-15 µm size range.

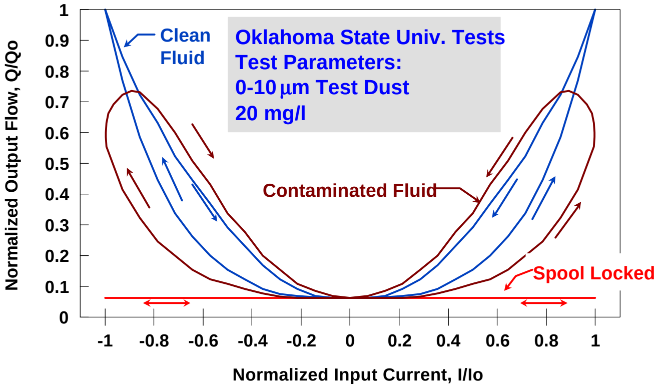

Figure 8. Contamination Effects on Hysteresis (OSU)

Black (Moog) [12] investigated the effects of contaminants on servovalve hysteresis and spool leakage. Figure 10 reproduced from the results of his study shows the increase in hysteresis with fluids contaminated with 0-10 µm fine test dust. Hysteresis increased with higher dirt concentrations, as shown, then upon filtering the oil to “clean” conditions, the hysteresis returned to its original value. Permanent degradation was noted in pressure gain (17% decrease) and null leakage (increase from an initial 3% to over 20% of rated flow).

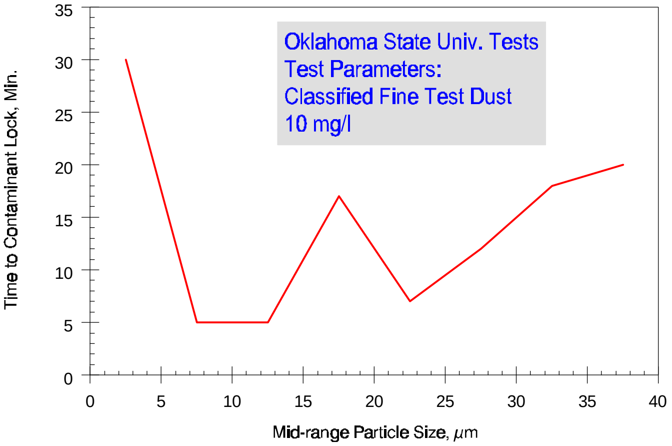

Figure 9. Silting Effect on Servovalves

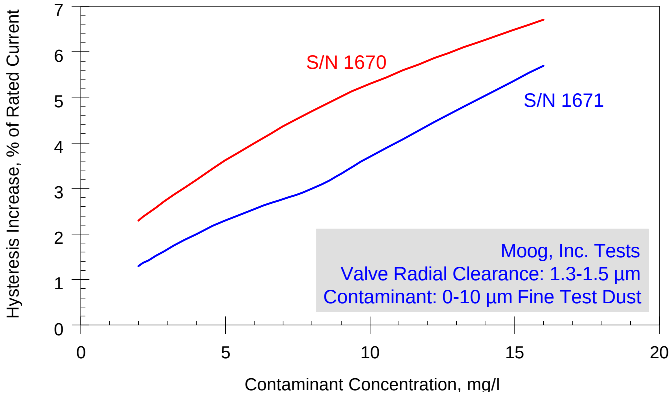

Figure 10. Contaminant Effects on Hysteresis (Moog)

The primary conclusions drawn from the studies noted is that servovalves are indeed sensitive to particulate contamination. Erosion, which affects pressure gain, flow gain, and null leakage is proportional to the number, size, velocity and relative hardness of the particles passing over the metering edges. Silting, which affects hysteresis (contaminant lock) and stability is proportional to the number of particles of size similar to the critical port or spool/sleeve clearance. The spool/sleeve radial clearance for typical servo actuators is in the 1-4 µm range; therefore, filtration and contamination control should be designed to minimize these size and larger particles.

Anti-Friction (Rolling Contact) Bearings - As illustrated in Figure 11, surface-originated fatigue begins when a particle bridges the film clearance and dents a surface, usually the inner race. During subsequent contacts, fluid is hydrostatically forced into fissures at the base of the dent, propagating a widening crack that eventually undermines the surface. Fatigue failures can result in loss of shaft control and fragmentation of the bearing. Problems are magnified because of secondary damage due to the multitude of hard particles generated during fatigue spalling.

The classic study in this field was performed by Macpherson [19]. He measured roller bearing fatigue life with various levels of oil filtration. As shown in Figure 12, using 3 µm filters produced a six times increase in bearing life over 40 µm filters.

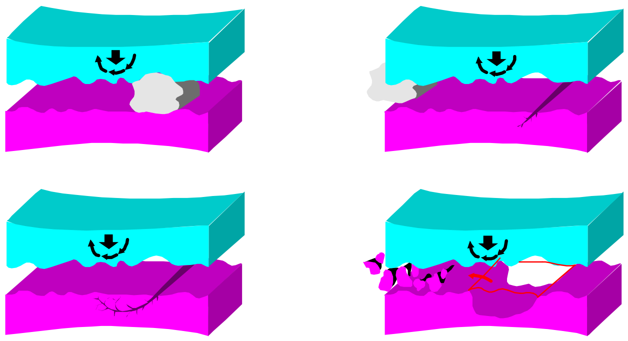

Figure 11. Contamination and Bearing Fatigue

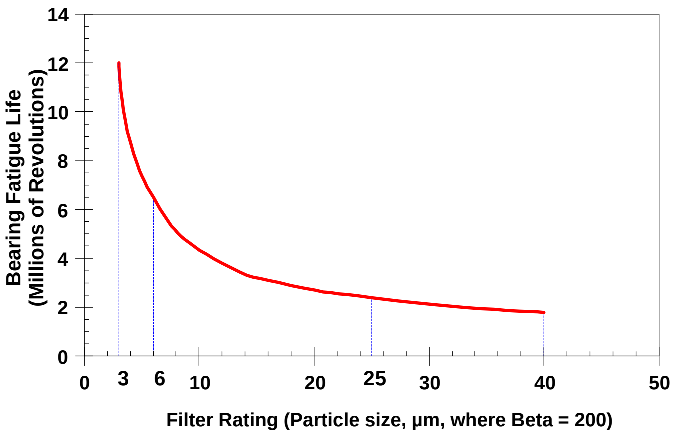

Figure 12. Macpherson Curve for Bearing Fatigue

STLE has recently published a handbook of life adjustment factors for rolling bearings [20], including the significant life factor of filtration, as shown in Figure 13. Note that both the Macpherson Curve and the STLE Curve show significant improvement only when filtration near 5 µm or better is reached. This conforms to the fact that rolling bearing film clearances are less than 1 µm and hence need extremely fine filtration in order to remove the majority of damaging particles.

Several leading bearing manufacturers have incorporated filtration and/or fluid cleanliness into life estimations of their products. Both SKF [21] and FAG [22] use a contamination factor for fatigue life designs. In addition, SKF literature asserts that by changing from contaminated to clean fluid, bearing life can increase up to 500 times. As well as allowing users to extend the life of their machinery, this type of information permits engineers to design reliable equipment with smaller and lighter components.

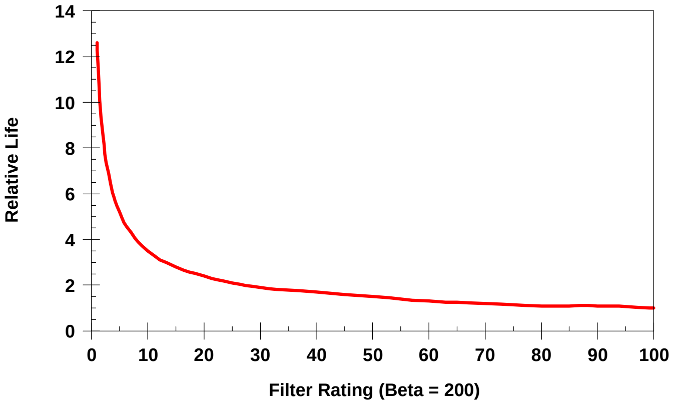

Figure 13. STLE Bearing Life Adjustment Factors

CONTAMINATION LEVEL RECOMMENDATIONS

Reducing the level of particulate contamination in hydraulic fluid is extremely important to achieve long life and high reliability. Operating contamination levels are a function of the efficiency and location of the system filters, system operating conditions, and contaminant ingression rates. Particulate contamination levels are generally expressed as a particle count per volume of fluid or as a Class/Code level as outlined in standards NAS 1638 [2], SAE AS 4059 [23], ISO 11218 [24] or ISO 4406 [25]. For the purposes of this paper, Classes per NAS 1638 (basically the same as AS 4059 and ISO 11218) are used. When necessary to convert from ISO 4406 to NAS 1638 (AS 4059), the minimum particle count corresponding to the ISO 4406 Code was used.

Industrial Standards - **The oil cleanliness specifications for industrial systems are generally cleaner than similar - though more critical - aerospace systems.** As an example, the industrial standard NFPA/JIC T2.24.1-1990 [26] states that filtration shall be provided for hydraulic systems with servo components to limit the in-service particulate contamination level to an ISO 4406 Code of 14/10 (NAS 1638 Class 4).

Several component manufacturers and industrial hydraulic system users have similar clean requirements. Table 3 is a list of typical industrial specifications for the maximum oil contamination level for systems containing servo components and/or rolling contact bearings. Generally the recommendation of the above specifications for the system filter rating is 3 µm or finer based on the industrial standard multi-pass filter test [31] for β=75 to 200.

Industrial Experiences - Using fine filters and proper contamination control techniques, it has been found practical and economical to routinely maintain systems at or better than NAS Class 3. There are numerous examples. A major Canadian airline employs fine, 3 µm (β_3 = 200) filtration on their flight simulators. They report fluid cleanliness levels at a Class 3-4; servos inspected after eight years of continuous operation show no visible signs of wear. At the General Motors Engineering Laboratory in Warren, Michigan more than 250 servo actuators have been protected successfully since 1986, using fine, 3 μm ($\beta_3 = 200$) filters, resulting in cleanliness levels measured with on-line automatic particle counters below Class 1 [32].

Table 3
Typical Industrial Cleanliness Specifications for Servo Controlled Hydraulic Systems and Bearings

Specification Source	Maximum Contamination Level per NAS 1638	Reference
NFPA/JIC (industrial machinery)	4	[26]
Saturn (automotive manufacturing)	4	[27]
BMW (automotive manufacturing)	4	[28]
STLE/CRC (bearings)	3	[29]
Vickers (hydraulic)	4	[30]
SKF (bearings)	4	[21]
FAG (bearings)	3	[22]

A large scale study of aircraft test stands in the UK in the 1980's [33] reported a typical cleanliness of Class 4. A more recent survey of samples (unfortunately with uncontrolled sampling and reporting techniques) from typically servo controlled robots, test machines and simulators reported a cleanliness Class 4-5 for 3 μm filtered systems and Class 2 for 1 μm filtered systems [34].

Large scale lubrication systems are also routinely maintained quite clean. As an example, International Paper [35] and Weyerhauser [36] report the contamination level in their paper machine lube systems to be at Class 3-5. These clean levels are achieved in spite of operating in a “dirty” environment and with large reservoir volumes of about 20,000 liters.

Aerospace Standards - Typical contamination levels recommended for commercial aircraft hydraulic systems are Class 8 or 9. Boeing Specification BMS 3-11 specifies a maximum Class 9 for newly delivered aircraft but has no specification for operating aircraft. Douglas specifies Class 8 for in-house aircraft systems and Class 9 for operating aircraft. Airbus specifies Class 7 for new fluid and Class 9 for their operating aircraft.

Several non-commercial manufactures of aircraft and related hydraulic equipment have published recommended contamination levels much cleaner than the typical Class 9 currently specified for commercial aircraft. As an example, SAE AIR 1918 [37], which contains the recommendations of ten aerospace companies, shows that two thirds of those reporting cleanliness requirements specified Class 5 or better. This and other aerospace recommendations are shown in Table 4.

Table 4
Cleanliness Specifications for Aerospace Hydraulic Systems

Specification Source	Maximum Contamination Class per NAS 1638	Reference
Douglas, Airbus	9	
SAE AIR 1918	67% recommend ≤ 5	[37]
Moog	5	[38]
Vickers	Aerospace -3 Aircraft - 4	[39]

Aerospace Experiences - Some commercial airlines have routine sampling programs to measure the particle count, moisture level, TAN, chlorine content and other properties of the hydraulic fluid. The NTSB in its Hydraulic Fluid Subgroup Report No. 95-44 [40] reported the contamination levels for several aircraft from various airlines. Table A of that report contains data for 98 samples from 21 Boeing 737 aircraft with levels reported for both reservoir and rudder PCU samples from “A” and “B” hydraulic systems.

Figures 14 and 15 illustrate the range of particulate contamination levels for the reservoir drain samples and rudder PCU samples respectively. Because the overall data from the “A” and “B” hydraulic systems were similar the data were all grouped together into the data reported in these figures. From these data it can be seen that the average contamination level is approximately Class 8 with range from Class 4 to 13. Some of the variation in results is undoubtedly due to sampling errors associated with drawing fluid into a bottle. However there is a tremendous scatter among aircraft from relatively clean to extremely dirty.

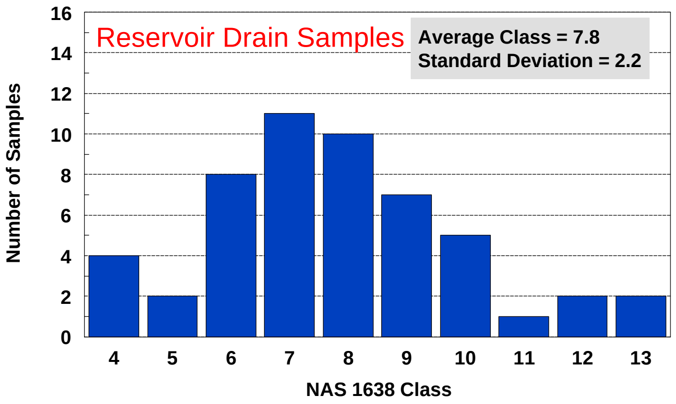

Figure 14. NTSB Data from Reservoir Samples

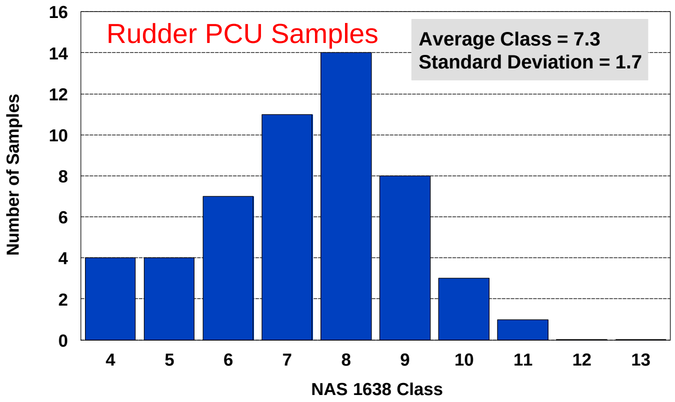

Figure 15. NTSB Data from Rudder PCU Samples

Another study of aircraft contamination levels was summarized in 1993 by Monsanto [41]. Their reports were based on hundreds of sample data extracted from Monsanto's fluid analysis program. The Monsanto data was divided into groups by aircraft type and by flight hours on the aircraft. No trends could be seen from the flight hour breakdown so all the data for each aircraft type are included in Table 5. These data are based on a grand average NAS Class for each aircraft type. The average particle count was calculated from the average NAS Class. It is interesting to note from these data that the three cleanest aircraft, B727, A300 and A310 could most likely have had some aircraft flying with one or more 3 µm filters in the system as 3 µm filters are qualified on these aircraft.

Table 5
Average Contamination Data from Monsanto Report

Aircraft Type	Average NAS 1638 Class	Average Particles per 100 mL > 5 µm
B727	6.3	24,000
B737	8.5	110,000
B747	7.8	66,000
B757	7.8	66,000
B767	7.0	39,000
DC8	7.3	48,000
DC9	7.6	60,000
DC10	8.1	85,000
A300	6.9	36,000
A310	7.3	46,000

A major test program on hydraulic contamination with controlled parameters and on-line particle counting was conducted in 1990 at McDonnell Douglas by Pall Corporation on an "iron-bird" 8000 psi tactical aircraft simulator. The simulator contained a mock-up aircraft hydraulic system containing two power control systems and a utility system. The purpose of the testing, through the use of on-line, real time automatic particle counting, was to ascertain fluid contamination levels during flight simulation using standard 5 µm filters per Mil-F-8815 as well as a finer 1 µm prototype filter. The flight sequence simulated was a two hour combat mission including, taxi, take-off, climb, cruise, combat, and return. It should be noted that almost all US Navy aircraft are protected by 5 µm absolute or finer hydraulic filters.

During the McDonnell Douglas testing, the median contamination level measured downstream of the 5 µm return filter was AS 4059 Class 00 and when the 1 µm filter was used, a Class 000 was obtained. The "real-time" hydraulic fluid contamination levels downstream of the return line filters varied throughout the mission as shown as an example in Figure 16. Although the hydraulic actuations on this fighter aircraft simulator are more severe than a commercial aircraft, one would expect the contamination level on a passenger aircraft to also vary during the various phases of flight. **The lowest contamination levels would be expected during low stress periods such as cruise and idle on the ground.** Unfortunately, this would also imply that the contamination levels reported during normal aircraft sampling, such as in Figures 14 and 15, would be lower than during flight and maneuvering.

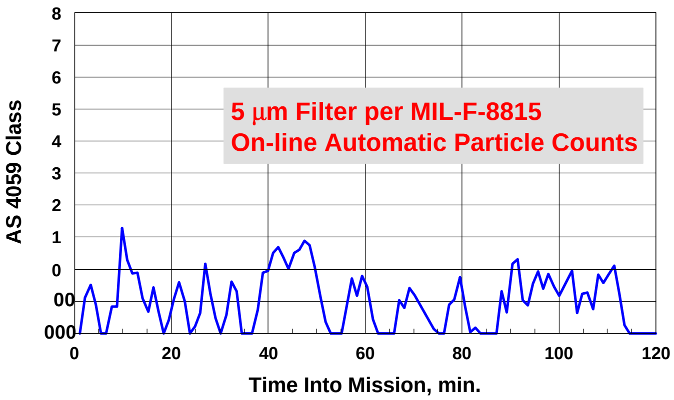

Figure 16. Particle Count Variation with Time

Target Cleanliness for Commercial Aviation - Aerospace systems are both critical and expensive, and the reliability requirements are enormous. Cleaner fluids equate to greater reliability and reduced maintenance costs. To obtain these benefits aviation hydraulic systems should be as clean or cleaner than levels recommended for and attained by similar industrial equipment. We therefore recommend that commercial aircraft hydraulic systems operate at a cleanliness of NAS 1638 Class 3 or cleaner.

This level of cleanliness will be achieved by improved contamination control - specifically, finer filters in the range of 1-5 µm, as determined by SAE ARP 1827 [42]. To minimize background contamination as well as to accommodate operators schedules, monitoring of cleanliness levels should be done with on-line automatic particle counters for rapid and accurate results.

SAMPLING AND MONITORING

SAMPLING METHOD - Drawing several ounces (50-100 mL.) of fluid into a bottle has been the standard sampling method for decades. Unfortunately, this procedure tends to detect background contaminants nearly as well as the system's. Problems confounding bottle sampling include: bottle cleanliness, ambient dust, extent of flushing of sampling port, and technique of the individual taking the sample.

To overcome these difficulties, on-line sampling methods have been developed. An automatic particle counting device such as pictured in Figure 17 is connected to a sampling port with quick-disconnects. Fluid flows from the inlet tubing through the sensor. To eliminate waste and disposal costs, the fluid is typically returned back to the system. Once connected, fluid is allowed to flush the circuit for several minutes, followed by about one minute of particle counting. This procedure eliminates problems of bottle sampling. It is also fast.

For clean systems, particle counts measured by on-line counting are often found to be several classes cleaner than those measured by bottle sampling. For example, during the McDonnell Douglas study reported above, bottle samples were on several occasions taken simultaneously with on-line counting. In all cases the on-line particle counts were two or more NAS 1638 Classes cleaner than the bottle counts.

Because of the remarkable accuracy provided by on-line counters, clean systems are no longer penalized by poor sampling methods, nor are contaminated systems pardoned for the same reason.

Figure 17. Portable On-Line Particle Counter

SAMPLING LOCATION - SAE ARP 4268A [43] describes several locations for a sampling port, including upstream of return line and case drain filters and downstream of pressure and return line filters. Two important factors are at work: 1) assessing: the number of damaging particles entering the system, and 2) accessing: conveniently available sampling sites. For these reasons we recommend that for commercial aviation systems, on-line particle monitoring be performed preferably with a permanently installed sampling valve in the pressure line or, alternatively, from a side sampling port on a pressurized reservoir. Sampling from a drain valve is not recommended.

SAMPLING FREQUENCY - SAE ARP 4268A recommends "initial sampling frequencies of 6 - 12 months or 1500 hours, whichever comes first." We suggest for commercial operators that periodic monitoring of particle count, using on-line counters, be performed at the beginning of an overnight maintenance check, such as a B-Check, but no less often than two times per C-Check. This would typically equate to sampling every 1500 - 2000 flight hours. This periodic sampling schedule provides suitable monitoring of system cleanliness as well as operator convenience. In addition, sampling should be performed after any occurrence of an uncommanded control-surface movement.

SAMPLING LOGISTICS - SAE ARP 4268A suggests that "hydraulic fluid samples should be taken as soon after landing as possible on aircraft, and after exercising the hydraulic system with ground power." We believe attempting to extract a sample during normal ground operations is impractical for commercial operators. A more pragmatic approach is to monitor particles as part of the regular maintenance procedures. During that time the system could be exercised and on-line counts conveniently obtained. In addition, if the target cleanliness level is exceeded, the system can be cleaned using a ground cart equipped with 1 µm filtration, or with a similarly equipped fluid purifier such as shown in Figure 18. This approach allows real-time detection and elimination of system contamination. Both counting and flushing are performed simultaneously with other maintenance activities. Thus both monitoring and immediate correction of non-comformances are completed without any disruption of passenger service.

Figure 18. Portable Fluid Purifier

By detecting and immediately correcting any contamination problems, this method also facilitates remediating any contamination deviations after an uncommanded control-surface movement.

EPILOGUE

Improved contamination control will increase aircraft hydraulic system reliability by significantly increasing the MTBR of hydraulic components. This includes preventing the silting of servovalves. Silting may cause stiction, an increase in hysteresis and slower response time. In extreme cases, unbalanced or jammed valve(s) may cause an uncommanded movement of a flight control surface if the surface is operated by a single actuator/valve combination.

Economic benefits of greater reliability include reducing unscheduled aircraft maintenance, thereby curtailing costly aircraft delays, air/ground turnbacks, cancellations, and diversions. Longer hydraulic component life will also result in reduced maintenance costs and faster return of aircraft to service, leading to more aircraft availability producing greater revenue.

The commercial aviation industry has a unique opportunity. Significant benefits can be achieved by operating with cleaner hydraulic fluids. Improved equipment performance and enhanced reliability are there for the taking. The target cleanliness level of Class 3 is currently found in a wide range of industrial equipment. Using currently available technology, Class 3 is feasible for aircraft.

CONCLUSIONS AND RECOMMENDATIONS

1. Studies find that fluid contamination degrades the performance, reliability, and life of mechanical components.
2. Silting of servovalves may cause stiction and slower response time. In extreme cases, unbalanced or jammed valve(s) may cause an uncommanded movement of a flight control surface if the surface is operated by a single actuator/valve combination.
3. Contamination levels in aircraft hydraulic systems vary greatly during flight maneuvers, with the cleanest fluid during cruise and at idle on the ground. Contamination levels during flight are likely to be greater than indicated by accurate samples obtained during ground idle.
4. Manufacturers and technical organizations are incorporating factors for contamination and/or filtration into rolling bearing life equations. It is suggested that manufacturers of aerospace hydraulic components do the same.
5. To improve life and performance of industrial hydraulic and lubricating equipment, many technical organizations and equipment manufacturers recommend system cleanliness levels of NAS 1638 Class 3 or 4.
6. Today, machines in many industries are operating at Class 3 or better.
7. It is feasible for commercial aviation hydraulic systems to operate at Class 3 or better. This can be achieved by filtration in the 1 - 5 µm range, per SAE ARP 1827.
8. When necessary on-board filters may be supplemented by cleaning (flushing) hydraulic circuits using fluid purifiers or hydraulic carts equipped with 1 µm or finer filters.
9. So as not to penalize clean systems with poor samples, on-line particle counting is recommended for obtaining accurate data at convenient maintenance intervals.
10. By increasing component MTBF, improved cleanliness will provide significant economic benefit to airlines.
11. To obtain the benefits of longer component life, it is recommended that commercial aviation hydraulic systems operate with a fluid cleanliness level of NAS 1638 Class 3.

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