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STRATEGIC IMPLEMENTATION AND COST/BENEFIT OF CONTAMINATION CONTROL

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ABSTRACT

Contamination control encompasses the subject of machine life and maintenance costs. This paper discusses the Life Extension Method (LEM), a program to extend the meantime between failures based on improved fluid cleanliness levels. The LEM provides a fluid cleanliness target as the first of three steps to implement a contamination control program. The complete implementation strategy is presented and discussed.

NOMENCLATURE

AF — Adjustment Factor. A number used to adjust the ingression rate at a specific Particle Size Focus.

APF — Airborne Particle Factor. The concentration of airborne particles near a machine.

CLI — Contaminant Life Index. One method used to assign a target cleanliness level that is machine specific. The CLI is a short series of questions that establishes the contaminant sensitivity of a machine in terms of design features, environment, and application. Setting a target cleanliness level is the first of three steps in a proactive maintenance program.

dCA — Digital Contam Alert. A battery operated, hand-held computer that provides hard particle counting for field use or in-house lab analysis.

FSC — Filter Selection Chart. A series of questions designed to assist in the selection of new or confirmation of current filtration systems.

GPM — Gallons Per Minute. A unit of measure for the rate of flow in a fluid.

ISO — International Standards Organization.

ISO Code — The ISO code is an international standard code for the contaminant level in a fluid. It indicates the number of particles greater than 5 microns/ml and the number of particles greater than 15 microns/ml.

LEM — Life Extension Method. A process that uses a chart to set the goal for extending the machine life span. Defines the initial step in proactive contamination control, by setting the target cleanliness level for a machine.

NFPA — National Fluid Power Association. They publish national standards on fluid power.

PSF — Particle Size Focus. The hard particle size, in micron units, that helps in filter selection.

RCL — Required Cleanliness Level. A fluid cleanliness goal derived for each machine, using the CLI or the LEM techniques.

SAE — Society of Automotive Engineers. A large national group, recognized world-wide for their various published standards.

n = efficiency of the filter at retaining particles above the PSF

N_u = concentration of particles upstream of the filter at PSF

Q = flow rate through the filter in GPM

Q_m = minimum flow rate in GPM

Ri = ingression rate associated with particles at and greater than the Particle Size Focus (PSF)

Wi = work-end ingression rate, which is a ratio of the number of particles at the "work-end" of the system to the ingression rate.

INTRODUCTION

For a maintenance program to be effective, the law of material balance must be observed. This premise states that for any amount of contamination that is ingested or generated within a dynamic or static system, an equal amount of contamination must be removed. The process to achieve this material balance is a function of each individual machine, environment, and application. This contamination control program must be achievable, logical, simple, and sequentially implemented as a process.

The basic objectives of any maintenance/contamination control program is to minimize maintenance costs, maximize machine life, and control and monitor all systems on a continual basis. Proactive contamination control accomplishes all of those objectives and also takes into consideration all of the aforementioned variables to achieve a material balance.

The following are three accurate and reliable steps to implement a proactive contamination control program that achieves the target improved fluid cleanliness:

1. Each system must have a target cleanliness set in terms of particle size and concentration. The cleanliness level is the goal or base line necessary to accomplish an extended machine life. This is done by using the Life Extension Method (LEM).

2. Proper selection and implementation of application and environment-specific filtration must be in place to achieve and maintain the necessary cleanliness level.

3. Proactive, on-site contaminant monitoring must be routinely performed to insure that target cleanliness levels are achieved and adjustments are made accordingly. Feedback is essential in a contamination control program.

All three of the aforementioned steps are dependent upon each other. One cannot be achieved without the other, or it will not accomplish the goals of proactive contamination control.

STEP ONE

Assessing System Target Cleanliness

Users of hydraulic or lubrication equipment need a starting point, which is - how clean does my fluid need to be and what relative life extension will be achieved? In other words, what are my contamination control targets or what are my limits? This starting point or cleanliness target, has not been readily available before, due to the fact that each machine is different and encounters a variety of operating conditions.

Life Extension Method

The strategic implementation of a contamination control program usually targets high fluid cleanliness levels, so that substantial machine cost savings are achieved. This program is called proactive maintenance, with the primary goal being machine life extension. The Life Extension Method (LEM) is the maintenance managers answer to machine life extension, thereby reducing maintenance costs. It is a procedure that assigns a target cleanliness level to a machine.

The LEM, see Figure 1, is a compilation of three different third party organizations that performed studies on machine contaminant sensitivity. The first table on hydraulic machines, was conducted by the British Hydromechanics Research Association (BHRA) and based upon 117 hydraulic systems over a three year period. Table II is a study of rolling contact bearings, done by Dr. P.B. Macpherson in conjunction with Westland Helicopter and the Imperical College. Several hundred bearings were tested and the results are known as the Macpherson curve. SKF, a prominent bearing manufacturer, conducted a

TABLE I
Hydraulic Systems: Required New Machine Cleanliness (C)

A: CURRENT MACHINE CLEANLINESS (ISO) \ B: Life Extension Factor	2	3	4	5	6	7	8	9	10
26/23	23/21	22/19	21/18	20/17	20/17	19/16	19/16	18/15	18/15
25/22	23/19	21/18	20/17	19/16	19/15	18/15	18/14	17/14	17/14
24/21	21/18	20/17	19/16	19/15	18/14	17/14	17/13	16/13	16/13
23/20	20/17	19/16	18/15	17/14	17/13	16/13	16/12	15/12	15/11
22/19	19/16	18/15	17/14	16/13	16/12	15/12	14/11	14/11	14/10
21/18	18/15	17/14	16/13	15/12	15/11	14/11	14/10	13/10	13/10
20/17	17/14	16/13	15/12	14/11	13/11	13/10	13/9	12/9	12/8
19/16	16/13	15/12	14/11	13/10	13/9	12/9	12/8	11/8	11/8
18/15	15/12	14/11	13/10	12/9	12/8	11/8	—	—	—
17/14	14/11	13/10	12/9	12/8	11/8	—	—	—	—
16/13	13/10	12/9	11/8	—	—	—	—	—	—
15/12	12/9	11/8	—	—	—	—	—	—	—
14/11	11/8	—	—	—	—	—	—	—	—
13/10	11/8(1)	—	—	—	—	—	—	—	—
12/9	11/8(2)	—	—	—	—	—	—	—	—

(1) Life Extension Factor = 1.8 (2) Life Extension Factor = 1.45

TABLE II
Rolling Contact Bearings: Required New Machine Cleanliness (C)

A: CURRENT MACHINE CLEANLINESS (ISO) \ B: Life Extension Factor	2	3	4	5	6	7	8	9	10
26/23	22/19	20/17	18/15	17/14	16/13	15/12	15/12	14/11	14/11
25/22	21/18	19/16	17/14	16/13	15/12	14/11	14/11	13/10	13/10
24/21	20/17	18/15	17/14	16/13	15/12	14/11	13/10	13/10	12/9
23/20	19/16	17/14	15/12	14/11	13/10	13/10	12/9	11/8	11/8
22/19	18/15	16/13	14/11	13/10	12/9	11/8	11/8	—	—
21/18	17/14	15/12	13/10	12/9	11/8	11/8	—	—	—
20/17	16/13	14/11	13/10	11/8	—	—	—	—	—
19/16	15/12	13/10	11/8	—	—	—	—	—	—
18/15	14/11	12/9	—	—	—	—	—	—	—
17/14	13/10	11/8	—	—	—	—	—	—	—
16/13	12/9	—	—	—	—	—	—	—	—
15/12	11/8	—	—	—	—	—	—	—	—
14/11	11/8(1)	—	—	—	—	—	—	—	—
13/10	11/8(2)	—	—	—	—	—	—	—	—
12/9	11/8(3)	—	—	—	—	—	—	—	—

(1) Life Extension Factor = 1.8 (2) Life Extension Factor = 1.5 (3) Life Extension Factor = 1.3

TABLE III
Diesel Engines: Required New Machine Cleanliness (C)

A: CURRENT MACHINE CLEANLINESS (ISO) \ B: Life Extension Factor	2	3	4	5	6	7	8	9	10
26/23	23/20	22/19	21/18	20/17	20/17	19/16	19/16	18/15	18/15
25/22	22/19	21/18	20/17	19/16	19/16	18/15	18/15	17/14	17/14
24/21	21/18	20/17	19/16	19/16	18/15	17/14	17/14	16/13	16/13
23/20	20/17	19/16	18/15	17/14	17/14	16/13	16/13	15/12	15/12
22/19	19/16	18/15	17/14	16/13	16/13	15/12	14/11	14/11	14/11
21/18	18/15	17/14	16/13	15/12	15/12	14/11	14/11	13/10	13/10
20/17	17/14	16/13	15/12	14/11	13/10	13/10	13/10	12/9	12/9
19/16	16/13	15/12	14/11	13/10	13/10	12/9	12/9	11/8	11/8
18/15	15/12	14/11	13/10	12/9	12/9	11/8	—	—	—
17/14	14/11	13/10	12/9	12/9	11/8	—	—	—	—
16/13	13/10	12/9	11/8	—	—	—	—	—	—
15/12	12/9	11/8	—	—	—	—	—	—	—
14/11	11/8	—	—	—	—	—	—	—	—
13/10	11/8(1)	—	—	—	—	—	—	—	—
12/9	11/8(2)	—	—	—	—	—	—	—	—

(1) Life Extension Factor = 1.9 (2) Life Extension Factor = 1.35

Figure 1

separate report and the results were similar to the Macpherson curve. The third table came from a study done by General Motors on diesel engines.

The following is a two step process to implement the Life Extension Method:

1. Determine Current Machine Cleanliness

Initially, one or more particle counts must be obtained from the machine. It is best if the sample is taken while the machine is operating normally. Avoid taking a sample immediately after an oil and/or filter change, because fluids can be abnormally clean. This particle count should be represented in the ISO solid contaminant code (ISO 4406). *(Example: an injection-molding machine was sampled and found to have an ISO contaminant level of 21/18.)*

2. Determine Extended Machine Life Cleanliness Level

To determine the extended life cleanliness level refer to Figure 1. There are three tables, each representing a different machine type. Use the appropriate table corresponding to the machine currently under evaluation. Table I is used for hydraulic systems, turbines, gear systems, and compressors. Table II is for rolling contact bearings. Table III is for diesel engines.

Begin by finding the current machine cleanliness, located in the far left column, within one of the respective tables. The rows to the right of the current machine cleanliness levels, are ISO codes that correspond to the extension factors in the very top row (two through ten). Determine the life extension factor that is to be achieved. Then follow that number down and the current cleanliness level over to where they meet. This new ISO code is the recommended cleanliness level for that particular machine. Repeat this procedure for each individual machine.

Note that a life extension factor of 5 means that the mean time between failure will be five times longer (500% longer) at the newly stated cleanliness level. Also note that fluid cleanliness levels ranging below ISO 11/8 are not given since filtration and particle counting below this level are generally prohibitive or unreliable.

(Example: using Table I in the example with a life extension factor of five and a current cleanliness of ISO 21/18, translates into a new fluid cleanliness target of ISO 15/12. This ISO 15/12 is the target cleanliness level for the injection-molding machine using the proactive maintenance LEM procedure.)

STEP TWO

Filter Selection

In the past, there has been a tendency to over-design, over-specify, and over-protect a system, when selecting a filter. This was done to compensate for a lack of expertise or precise, adequate information on machine requirements. Many times the filter selection decisions are placed in the hands of an eager filter salesman boasting of dubious filtration expertise. A good example of this is when companies publish recommendations for system cleanliness without specific machine information on component sensitivity, the application, or environment severity. Another common practice, is when a filter company gives a filter recommendation without previously determining the required target cleanliness level of each particular machine.

A more scientific approach has been suggested, where the "critical clearances" between the moving and sliding parts of the system become the determining factor when selecting filters. It is apparent that these clearances effect contamination sensitivity, but it can be more misleading than helpful in many cases. In most systems these clearances tend to vary (1) during operation, (2) during component life, and (3) from component to component within a single system. They also fail to take into consideration the system's pressure, ingression rate, surge flow, and filter location.

The most popular type of "scientific-guess work" in filter selection techniques are those that depend upon life-cycle field experience. Many times, large equipment manufacturers will design in components that are known to function with very contaminated fluids and have therefore become forgiving of poorly selected filtration. Other times equipment manufacturers have selected filtration based solely on field experience. In these cases, the filter selected is usually over-specified (overkill) or the life of the equipment components could be extended many times by improving filtration only slightly.

The Filter Selection Process

In any controlled or controllable system, there is an orderly or systematic sequence of rules that must be followed. Remember, contamination control follows the premise of material balance (i.e. particles entering a system (ingression) less particles removed (filtration) should leave (what remains) a system's required cleanliness level.) Since particles over a certain size, at a specific cleanliness level, should not increase over time, then the particles entering should equal the particles exiting.

The logical expansion of the three step contamination control program is as follows:

1. Using the aforementioned LEM method, determine the required cleanliness level in terms of particle count concentrations and particle size, e.g. the ISO code, then;

2. establish the critical particle size benchmark; above which, particle counts must be controlled by filtration at a required level, then;

3. determine the ingression rate above the critical particle size under normal field and application conditions, then;

4. taking into consideration the field and application severity, identify the filter location, flow, and efficiency that will offset, with an adequate margin for error, the specified ingression rate, then;

5. proactively monitor fluid cleanliness, on-site, to verify that the required cleanliness is achieved, and finally;

6. assess the machine life-cycle and reliability performance over time confirming the correctness of the selected critical particle size and cleanliness level benchmarks.

The Filter Selection Chart

The Filter Selection Chart (FSC) extends the LEM through a series of questions for a complete filter selection process. Essentially it is a step-by-step rule-based technique that can be applied to a variety of machine applications. Listed below are the instructions and explanations for each FSC section. See Figure 2.

Particle Size Focus

When selecting a filter, the Particle Size Focus (PSF) is first determined from the Required Cleanliness Level (RCL), using the 100-count rule. This RCL was previously established using the LEM technique. Refer to the following steps to determine the PSF:

1. Plot the RCL's particle size distribution on the chart in Figure 2, part I. A straight or near straight diagonal line should result.

2. At the point where the RCL line and the 100-particles-greater-than-10-microns horizontal line cross, draw a vertical line, starting at the intersection point and proceed straight down.

3. The PSF is then identified where this vertical line crosses the particle size scale in microns. Or, using only the target ISO code, the table to the right of the chart can be used. *(Example: the LEM value of 15/12 for the injection-molding machine, yields a particle size distribution corresponding to a PSF of 8 microns.)*

Only after identifying the PSF can the efficiency of the filter above that specified size be determined. It can be argued that a filter with a Beta 10 of 100 is really just a 3 or 6 micron filter in disguise. The Beta 10 of 100 means that for every 100 particles 10 microns and larger, only one of those 100 particles get through the filter. The 3 or 6 micron filters are able to remove these smaller sized particles with at least a nominal efficiency. The application of high Beta rated filters, in some

Filter Selection Chart (FSC)

Machine ID	CLI or LEM Score	Date

For Specifying Filters

I. Particle Size Focus

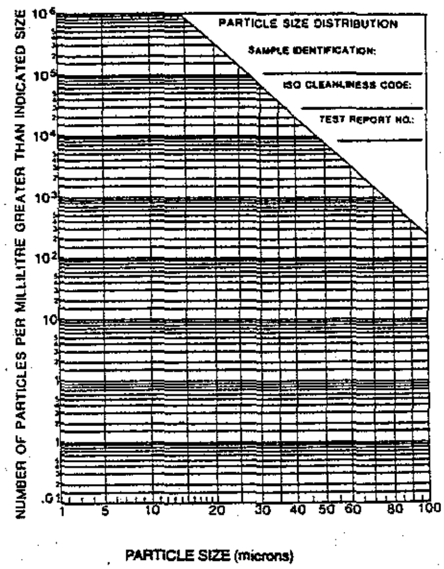
1) Plot target particle size distribution (based on CLI or LEM value) on graph at far right.
2) Draw vertical line down from point at which distribution line crosses 100-count line.
3) The corresponding size in microns (μm) is the particle size focus.
4) Alternatively, use Table A to the right.

TABLE A

Target ISO CODE	PSF (μm)
21/18	38
20/17	31
19/16	25
18/15	20
17/14	15
16/13	11
15/12	8
14/11	5
13/10	3
12/9	1

OR

Particle Size Focus (PSF) ______ μm



II. Ingression Rate Estimation

(1)

Airborne Particle Factor (APF) — Circle correct value	APF Value
Very High - Underground mining, Rock quarries, Foundries, etc.	10
High - Road construction, Open-pit mines, Steel mills, Farming, etc.	8
Medium - Over-the-road trucks, Logging, Heavy mfg., etc.	6
Low - Medium/light industrial, Controlled indoor environments	3
Very Low - Filtered air, Clean room environments	1

(2)

Cylinder Wiper Seal Ingression — Consider No. Cylinder of stroke, rod size, mean cycle rate, wiper seal protection.	Cylinder Value
Very High - Large excavators, Scrapers, Cont. miners, Fellerbunchers, Systems >400 H.P.	100
High - Loaders, Combines, Crawlers, Systems 200 - 400 H.P.	75
Medium - Farm tractors, Large machine tools, Systems 50 - 200 H.P.	50
Low - Industrial and Stationary machines	25
Very Low - No cylinders	0

Cylinder Score = Cylinder Value x APF Value → ______ **A**

(3)

Reservoir Breather Ingression	Breather Value
Sealed Breather	0
8μm >10 Breather Filter	0.1
8μm >4 Breather Filter	0.3
8μm >2 Breather Filter	0.5
No Protection	1.0

Breather Score = Breather Value x APF x Cylinder Value → ______ **B**

(4) **Generated Particles — Add CLI Scores Sections, A, B, C, D, F, G**

Score: Multiply Total by 0.5 → ______ **C**

(5) **Total Ingression Score — Add A + B + C above** ______ **D**

(6) **Work-End Ingression Score (W,) = $\frac{A+C}{D}$** Enter W, value → ______ **E**

(7)

Ingression Rate — Circle Corresponding Ri(10) Value				
Ri(10)		**Total Ingression Score(D)**	**Ri(10)**	**Ingression Score(D)**
10^4	Particles >10 μm / min.	1 - 333	10^8	1334 - 1666
10^5		334 - 666	10^9	1667 - 1999
10^6		667 - 999	10^{10}	2000 - 2333
10^7		1000 - 1333	10^{11}	2334 +

(8) Use this conversion table below to determine ingression rate at Particle Size Focus (PSF)

Particle Size Focus (PFS)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Adjustment Factor (AF)	12.2	9.7	6.9	4.9	3.6	2.7	2.0	1.6	1.3	1.0	.81	.66	.55	.46	.38	.33	.27	.24	.20	.17	.15	.13	.12	.10	.08

Adjusted Ingression Rate Ri (PSF) = AF x Ri(10) → ______ **F**

Example: *PSF = 3μm* *Ri(10) = 10^7* *Ri (3μm) = 6.9 x 10^7 particles >μ m/ml*

Figure 2

III. Minimum Filter Flow Rate Estimation — Select From Filter Performance Table Below (in GPM)

Ingression Rate [(Ri(PSF)]

Wi, Fraction Of Ingression Entering At System Workend (i.e., not at tank breather) — Wi \ Ri	10^4	10^5	10^6	10^7	10^8	10^9	10^{10}	10^{11}
0	0.029 * 0.027 0.027 0.026	0.29 0.27 0.27 0.26	2.9 2.7 2.7 2.6	29 27 27 26	290 270 270 260	2900 2700 2700 2600	29000 27000 27000 26000	290000 270000 270000 260000
0.1	0.027 0.024 0.024 0.024	0.27 0.24 0.24 0.24	2.7 2.4 2.4 2.4	27 24 24 24	270 240 240 240	2700 2400 2400 2400	27000 24000 24000 24000	270000 240000 240000 240000
0.2	0.024 0.021 0.021 0.021	0.24 0.21 0.21 0.21	2.4 2.1 2.1 2.1	24 21 21 21	240 210 210 210	2400 2100 2100 2100	24000 21000 21000 21000	240000 210000 210000 210000
0.3	0.021 0.019 0.019 0.019	0.21 0.19 0.19 0.19	2.1 1.9 1.9 1.9	21 19 19 19	210 190 190 190	2100 1900 1900 1900	21000 19000 19000 19000	210000 190000 190000 190000
0.4	0.019 0.016 0.016 0.016	0.19 0.16 0.16 0.16	1.9 1.6 1.6 1.6	19 16 16 16	190 160 160 160	1900 1600 1600 1600	19000 16000 16000 16000	190000 160000 160000 160000
0.5	0.016 0.014 0.013 0.013	0.16 0.14 0.13 0.13	1.6 1.4 1.3 1.3	16 14 13 13	160 140 130 130	1600 1400 1300 1300	16000 14000 13000 13000	160000 140000 130000 130000
0.6	0.013 0.011 0.011 0.011	0.13 0.11 0.11 0.11	1.3 1.1 1.1 1.1	13 11 11 11	130 110 110 110	1300 1100 1100 1100	13000 11000 11000 11000	130000 110000 110000 110000
0.7	0.011 0.0083 0.0081 0.0080	0.11 0.083 0.081 0.08	1.1 0.83 0.81 0.8	11 8.3 8.1 8.0	110 83 81 80	1100 830 810 800	11000 8300 8100 8000	110000 83000 81000 80000
0.8	0.0082 0.0056 0.0054 0.0053	0.082 0.056 0.054 0.053	0.82 0.56 0.54 0.53	8.2 5.6 5.4 5.3	82 56 54 53	820 560 540 530	8200 5600 5400 5300	82000 56000 54000 53000
0.9	0.0056 0.0030 0.0028 0.0027	0.056 0.03 0.028 0.027	0.56 0.3 0.28 0.27	5.6 3.0 2.8 2.7	56 30 28 27	560 300 280 270	5600 3000 2800 2700	56000 30000 28000 27000
0.95	0.0043 0.0017 0.0015 0.0013	0.043 0.017 0.015 0.013	0.43 0.17 0.15 .13	4.3 1.7 1.5 1.3	43 17 15 13	430 170 150 130	4300 1700 1500 1300	43000 17000 15000 13000
0.97	0.0037 0.0011 0.00093 0.00082	0.037 0.011 0.0093 0.0082	0.37 0.11 0.093 0.082	3.7 1.1 0.93 0.82	37 11 9.3 8.2	370 110 93 82	3700 1100 930 820	37000 11000 9300 8200
0.99	0.0032 0.00061 0.00040 0.00029	0.03 0.0061 0.004 0.0029	0.3 0.061 0.04 0.029	3.0 0.61 0.4 0.29	30 6.1 4.0 2.9	300 61 40 29	3000 610 400 290	30000 6100 4000 2900
1.0	0.0029 0.00035 0.00013 0.000026	0.029 0.0035 0.0013 0.00026	0.29 0.035 0.013 0.0026	2.9 0.35 0.13 0.026	29 3.5 1.3 0.26	290 35 13 2.6	2900 350 130 26	29000 3500 1300 260

*1st Number corresponds to a 90% efficient filter ($\beta = 10$)
2nd Number corresponds to a 98.7% efficient filter ($\beta = 75$)
3rd Number corresponds to a 99.5% efficient filter ($\beta = 200$)
4th Number corresponds to a 99.9% efficient filter ($\beta = 1000$)

Minimum Flow Rate | GPM | **G**

IV. Minimum Filter Beta Ratio

(10)

β Ratio Selection Table - Circle value based on flow conditions	**β(PSF) =**
No Pressure/Flow Cycling	≥ 10
Occasional Pressure/Flow Cycling	≥ 40
Regular Pressure/Flow Cycling	≥ 75
Frequent and Severe Pressure/Flow Cycling	≥ 200

Minimum Beta | **H**

cases, may be less attractive if their performance was reported across a range of particle sizes.

Contaminant Ingression Rate Estimation

Estimating the contaminant amount being ingested into a hydraulic system, requires the evaluation of two major entry points, namely the cylinder wiper seals and the reservoir breather. First, the airborne particle concentration in the vicinity of the machine needs to be estimated, since it is these airborne particles that permeate breathers and stick to cylinder rods. It is easier and less costly, if the contamination can be removed from the air before it has a chance to ingress into the system.

The Airborne Particle Factor (APF) is selected from Table II(1) in Figure 2 based upon the user knowledge of the machine application environment. *(Example: the injection-molding machine scores a "low" with an APF of 3).*

Once the APF is determined, the next step is to evaluate the ingression from the wiper seals (for hydraulic systems). Wiper seals are designed to clean any debris off the cylinder rod (with a wiping action) as it retracts into the cylinder. Taking into consideration the effects of time, heat, and use, these seals tend to lose their effectiveness, allowing contamination to enter the system. In most cases, even new cylinders are not able to effectively keep out wiper-seal ingression.

The amount of contamination that enters a system from wiper seals depends heavily upon the number of cylinders, length of an average cylinder stroke, average rod size, and average cycle rate in the application. Rating the wiper seal ingression relies extensively on the user's knowledge of the equipment and the work pattern.

The Cylinder Ingression Table II(2) proposes suitable values for various equipment types and power plant ratings. If the representative value seems inappropriate, based upon the user's judgment or experience, then adjustments should be made. *(Example: the injection-molding machine rates a "low" cylinder ingression value, which seems appropriate for this type of equipment.)* The cylinder ingression score is determined by multiplying the cylinder value by the APF value and recorded into box **A**. *(Example: 25 x 3 = 75)*

In most cases, the breather is the most probable point for contamination to enter. When the volume in the reservoir changes due to cylinder extension (in hydraulic systems), air is let in. This air will transport contamination into the fluid, unless an efficient reservoir breather is installed. Unlike the cylinder wiper seals, contamination ingresses through the breather 24 hours a day, because of the thermal convection of air caused by temperature differences between the tank interior and the surrounding air.

A majority of the ingression through a breather can be prevented with minimal effort and expense. A standard spin-on filter can be inverted on an adapter post to serve as an efficient breather. This does not give the best protection when compared to a sealed breather/tank, but it is better than no filter at all.

To assess the breather ingression value, the Beta ratio for any existing breathers must be known. If the existing breather is sealed or does not even exist, the Breather Value Factor is easily defined from the Reservoir Breather Ingression Table, Figure 2, Part II(3). For all existing breathers, the Beta micron size becomes the Particle Size Focus (PSF) greater than one of the three efficiency choices listed in the chart (10, 4, 2). The respective Breather Value is then multiplied by the APF and the total is multiplied by the cylinder value to equal a breather score **B**. Please note that the extent of cylinder use will greatly impact the breather ingression rate. *(Example: injection-molding machine has PSF=8, with a Beta ratio of ten at eight microns, the breather value is 0.1, and the calculation for box* **B** *is 0.1 x 3 x 25 = 7.5)*

Generated Particle Ingression Rate Estimation

The ingestion of contamination from the environment will accelerate the process of particle generation internally. This "generated" contamination is usually the result of wear and corrosion debris. The impact that this process has on the health of a machine and the rate of occurrence, depends largely upon the sensitivity of the machine, contaminant wear and the application severity.

This Generated Particle section will be addressed later in the Empirical Ingression Rate Estimation. Alternatively, part II(4) can be done using another question based process called the Contaminant Life Index (CLI), but for now leave this section blank.

The Total Ingression Score, part II(5), can be skipped for now, unless using the CLI as mentioned before. With the CLI method, the system total ingression can be obtained by adding the values from boxes lettered **A**, **B**, and **C**. This combines cylinder and breather particle ingression with the internally generated contamination. *(Example: the total ingression score is entered into box* ***D****.)*

Work-End Ingression Estimation

Filters are usually placed downstream of the major ingression points, where they will be most beneficial. In these cases, the filter is exposed to higher particle concentrations; therefore, achieving higher particle removal rates. The other added benefit of having this filter location, is that particles are being eliminated from the system quickly, before they can spread throughout the system causing damage downstream.

To help in the filter selection, the work-end ingression score (Wi) is calculated in part II(6). This Wi calculation is the ratio of the number of particles ingested at the "work-end" of the systems, to the total ingression rate (including the amount of ingression at the reservoir). When the Wi ratio is greater than 0.50, more than half of the particles are entering from the cylinders and/or are being generated by the components.

This Wi score helps to evaluate the benefit of pressure line and return line filters. A low Wi ratio demonstrates the need for using suction line or off-line filters. The Wi ratio will also play a key role, later, in determining the required filter flow rate.

To figure the Wi ratio, simply take the value of **A** from part II(3) add it to **C** from part II(4) and divide that by the value of **D** from part II(5). Proceed now, to the Empirical Ingression Rate Estimation section if the CLI is not being used.

Empirical Ingression Rate Estimation

Whenever possible, the empirical technique should be used because it is a more direct means of inferring ingression rate. The empirical technique involves sampling the fluid during a typical work cycle in a typical work environment. This fluid sample must be taken from the return line, upstream of the return line filter (if one exists). Simultaneously, a sample must be taken (although difficult) at or near the suction line before the strainer. A sample from the reservoir, near the suction line may be used in its place. The difference between these two samples, correcting for flow rates, equals the ingression rate. If the return line sample (A) and the suction line sample (B) are described as particles greater than the PSF per milliliter, then the ingression rate is as follows:

$Ri\,(PSF) = 3785\,(A - B)\,Q$

Q is pump and return line flow rate in GPM.

The empirical technique does not take into consideration the breather ingression (where applicable), so this will still need to be estimated from part II(3) and added to the work-end ingression rate using the previously described method. Once the aforementioned equations are solved, place the answer in part II(6). Also, improved filtration, evolving from this filter selection process, will likely reduce generated ingression levels. This can not be empirically determined until the new filter is in place.

In place of the above method, an alternate empirical technique can be used. This technique involves the sampling of fluid upstream and downstream of the system filter(s) during normal working cycles. The particles removed, per unit of volume, are multiplied by the flow rate, giving a rough indication of the ingression rate. This technique is most reliable when a high efficiency, non-desorbing filter is in use.

Either one of the empirical techniques will provide the solution for **A + C** in the Filter Selection Chart (FSC). This means part II(4) should be skipped and part II(5) is, the empirical ingression number after adding the breather ingression from box **B** is the total ingression scored, box **D**. Part II(6) now becomes the empirical ingression value as the numerator and the answer from box **D** stays the denominator.

Ingression Rate/PSF Adjustment

It is now time to determine the rate at which particles are entering the system per unit of time, i.e. the ingression rate Ri(10) for particles 10 microns and larger. To figure the Ri(10), refer to the chart in part II(7). Using the Ingression score, **D** from part II(5), find that number on the chart and cross it over to the Ri(10) exponential number. *(Example: injection-molding machine's empirical ingression value of 878 yields an Ri (10) = 1 x 10^6 particles greater than 10 microns entering the system each minute).*

For this to have any significance in terms of filter selection, the Ri(10) must be adjusted to reflect the number of particles entering the system (ingression rate) compared to the particle size focus (PSF). This correction can be made by using an Adjustment Factor (AF), from the table located in part II(8). *(Example: the PSF is 8 for the injection-molding machine. The AF will be 1.6, making the correct ingression rate Ri(8) equal to 1.6 x 10^6 = particles per minute).*

Minimum Flow Rate Determination

The contaminant steady-state equation for a circulation system is:

Ri = NuQn, where

Ri = ingression rate at PSF

Nu = particle concentration upstream of the filter at PSF

Q = flow rate through the filter

n = efficiency of the filter at retaining particles above the PSF

If an off-line filter is in use, the Nu value is the same as the "blended" reservoir concentration. This off-line filter represents the lowest inlet concentration of any filter location.

An off-line filter is a low pressure circulating loop system, that pulls fluid from the tank by a pump, pushes it through the filters, and finally returns it directly into the tank (reservoir). This off-line filter is a constant-flow, multipass loop where no particle ingestion occurs in the circulating loop itself. Some examples of these off-line filters are full-flow engine lube filters, gear system filters, bearing filters, and side-flow hydraulic filters.

Filters located in the work-end of a hydraulic system are going to have higher inlet concentrations than that of off-line filters most of the time, due to the work-end ingression. Filters that are located where inlet concentrations are low, from the steady-state equation, must be compensated with higher filter flow rate and/or efficiency. Conversely, a lower efficiency filter can, to an extent, be tolerated where flows are high (and hopefully steady) and filter inlet concentrations are high.

The primary ingression points and filter locations impact region cleanliness relative to the recommended cleanliness levels. Therefore, filters can be strategically located to take advantage of known ingression sites and "critical required cleanliness" components. Such strategically located filters as pressure line and servo valve filters, used in combination with an off-line filter or return-line filter, should serve more to protect downstream contaminant sensitive, critical components than to provide the major point of particle removal (offsetting ingression rates). Components will benefit from longer service life and a lower net cost of filtration when this approach is implemented properly. These benefits are accomplished through the replacement of the lower cost return-line and off-line filters versus the higher-costing pressure line and servo filters.

It is essential to consider filter location when determining the minimum acceptable flow rate through a filter that is designed for removing ingression particles. In off-line and pressure line filter locations, it is assumed that the required cleanliness level (RCL) determined by the LEM, is logically the same as the inlet concentrations to the filter, i.e., the tank concentrations. Both the off-line and pressure line filters draw fluid directly out of this tank. There is no protection (filter) between the reservoir and the main system pump. This lack of protection subjects the main system pump to the tank concentration, thus making it logical to set the RCL at the tank.

Using this approach, a minimum filter flow rate for an off-line and pressure-line filter is described below, where:

RCL = Nu

RCL = required cleanliness level, i.e. 100 particles > PSF, from the 100-count rule.

Nu is 100 particles > PSF/ml per the 100-count rule, and Qm is in GPM. The minimum flow through the filter is:

$$Qm = \frac{Ri}{n(3785 \times Nu)} \quad \text{(1) Off-line}$$

$$Qm = \frac{Ri\,(1\text{-}0.3n)}{n(3785 \times Nu)} \quad \text{(2) Pressure line}$$

For a return-line filter, the downstream concentrations (entering the tank) added to the breather ingression rate must not exceed the required cleanliness level (RCL). This guarantees that the combination of the after-filter return line and the particles from the breather, when blended, do not reach the main system pump at a concentration above the RCL, providing protection for the most critical component.

Now, calculating the minimum flow rate through a return-line filter can be accomplished by establishing the Nu value as equal to the RCL plus the work-end ingression, previously determined:

$$Nu = \frac{Wi\,(Ri)}{Qm(3785 + RCL)}$$

Solving for Qm, for a return-line filter, the minimum flow rate equation is:

$$Qm = \frac{Ri\,(1 - nWi)}{n(Nu\ 3785)} \quad \text{(3) Return line}$$

The Filter Performance Table, part III simplifies the minimum flow rate calculation for all filter locations. Each block of the table has four flow rate values corresponding to filter efficiencies starting with 90%, 98.7%, 99.5% and 99.9% respectively (i.e., the efficiencies corresponding to Beta Ratios of 10, 75, 200, and 1000). The Ri, ingression rates, are listed across the top of the table and the Wi, work-end fraction, runs down the left side of the table.

For an off-line type filter (including engine, bearing, and gear system filters), use the first row of flow rate numbers being, Wi=0; since there is essentially no ingression between the tank and the filter. For pressure-line hydraulic filters, use the Wi row at 0.3 since the pump wear debris ingression can sometimes exceed 30% of the total ingression value. Actually, there is very little difference between minimum flow rates in the range between Wi=0 and Wi=0.3.

For the return line filters, use the calculated Wi value, from part II(6), and the Ri to find the minimum flow rate through the filter. Notice that the filter efficiencies above 90% have very little impact on minimum flow rates at Wi values below 0.9. The point at which Wi equals 1.0, the filtration process begins emulating a pure single-pass filtration system. Any hydraulic systems having sealed reservoirs should use the Wi=1.0 for return-line filters.

The Filter Performance Table serves as a guide to confirm or select adequate filter flow (above an indicated minimum level) and filter efficiencies. The alternative to using the Table, is to use the equations provided. It is recommended that minimum flow rates corresponding to 90% efficient filters (the first number in each box) be used for pressure-line and return-line hydraulic filters. The reasons for this recommendation will be described later.
(Example: the injection-molding machine, using the Filter Performance Table, a pressure-line filter would have a required minimum flow rate of 21 gpm by rounding up to a 10^7 ingression rate. Using the equation (2), the exact minimum flow rate value of 5.7 gpm without rounding, is calculated. For a return-line filter, with Wi equal to 0.8, the Qm is 8.2 gpm according to the table. Using the equation (3) the exact value of 2.2 gpm is obtained. In both calculations, the filter efficiency used is 90%)

<u>Determining the Required Filter Efficiency (Beta Ratio)</u>

ISO 4572, NFPA T3.10.18.8, and SAE J1858 standards call out multipass (efficiency) test procedures (Beta Ratios), which have only a limited correlation to filter performance in the field. This is due to the fact that filters in the field are subjected to different contaminants, flow, fluids, and temperatures than in these test procedures, with very few exceptions. One of the most important points is that the aforementioned standards do not measure the effects of pressure and flow cycling on filtration efficiency. However, it must be emphasized that the differences between field conditions and the multipass procedure, do not diminish the benefit and application of multipass testing for hydraulic filters. It is too difficult for standards committees to realistically design test procedures that encompass all possible field conditions.

The multipass filter test procedure (Beta) gives the efficiency of the filter under steady flow and pressure conditions. When selecting a filter for field use, the severity of pressure/flow cycling must be considered. Figure 3 demonstrates the effect that dynamic conditions have on performance.

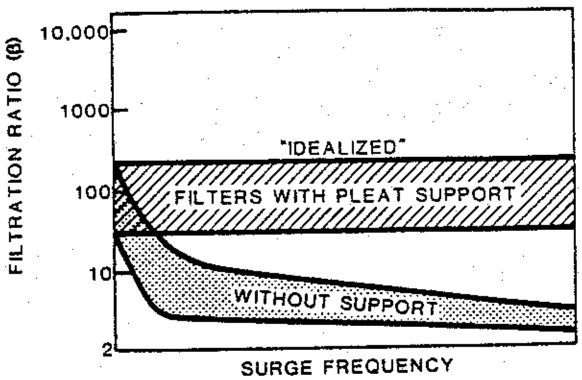


Figure 3

In Figure 4 we can see the benefit provided by filters supported by wire cloth when under a surge flow.

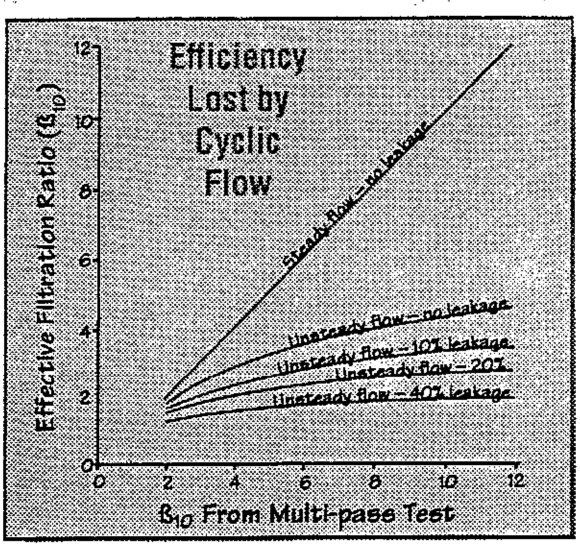


Figure 4

Off-line filters, including engine, bearing, and gear system filters, are least affected by field conditions since they usually operate under steady flow and pressure. Multipass efficiency data (Beta) is more reliable in these particular applications, allowing filters to be more precisely selected from the filter performance chart. In the case of pressure-line and return-line filters, the situation is different.

For these types of filters, the final step in selecting proper filtration, is matching the operating conditions of the filter location with the filter's performance integrity. The filter's Beta rating is extremely useful in this matching procedure. Filters that are subjected to high flow surge and/or pressure cycling require the performance integrity that a high-beta filter provides. Part IV(10) shows a table that translates field conditions to the corresponding recommended minimum Beta ratio. *(Example: the injection-molding machine, return line filter, has a required Beta Rating of 75 due to the extreme flow surges generated from cylinders.)*

Contaminant Exclusion

The proper filtration can be an effective attack against contamination, but continuous efforts should always be made to restrict its entry. The practice of contamination exclusion significantly reduces the cost of contamination control and contaminant level volatility. Figure 5 lists several options for contaminant exclusion.

STEP THREE

Field Verification of Filter Selection and Contamination Control

The final step to proactive contamination control maintenance is the monitoring of system contaminant levels. Monitoring of system fluids is the operative control element to achieving successful filter selection and contamination control. It has been proven that machine ingression levels can be difficult to predict and often they are much higher than acceptable. When filters are inadequate, due to low flow and/or high ingression rates, contaminant levels can rise orders of magnitude over a very short period of time, such as a few days.

Fluid contaminant monitoring closes the loop of contamination control by providing the essential feedback and control, giving integrity to the proactive contamination control program. The fluid contaminant monitoring can be done in the field or plant by extracting fluid samples into bottles for lab analysis or by portable instruments used directly on the machine. Recently, there has been a trend away from routine lab analysis through bottle sampling, due to the higher cost, reduced accuracy, and slower response time involved. Portable monitors that extract fluids directly out of the machines for real-time analysis, have been taking their place.

One such instrument, sold by Diagnetics, called Digital Contam-Alert (dCA), is battery operated and extremely lightweight. The components include a sensor attached by cable to a hand-held Computer. During a test, the sensor is placed momentarily on a special diagnostic port permanently installed on the machine. A small sample of fluid, under pressure from the machine, passes into the sensor and after a minute or two, the particle count is displayed on the computer screen. See Figure 5.

The unit can be used with a variety of different fluids, such as lube oils, hydraulic fluids, transmission fluids, gear oils, and coolants. After each test the handle on the sensor is depressed, expelling the fluid sample, and making it immediately ready for reuse. Particle count data can be easily stored in the computer, tagged to machine I.D., the date, and user comments. Later, the data can be printed out with a portable printer or it can be down-loaded to a desk-top personal computer.

Use of the portable contaminant monitor provides easy in-plant or in-field proactive or predictive maintenance. Maintenance operators can simply walk from machine to machine checking fluid contaminant levels while comparing them to target benchmarks. Maintenance work orders can then be issued to correct any out-of-spec machines.

Figure 5

SUMMARY

Proactive contamination control is steadily becoming a standard practice in maintenance strategies, because of its ability to extend machine life, reduce maintenance costs, and employ regular condition monitoring. With these objectives in mind, this program can be implemented in three easy steps, (1) determine the required cleanliness level using the LEM, (2) select and install proper filtration, with the FSC, to achieve the target cleanliness level, and (3) frequently monitor fluid contaminant levels for feedback. These tools are providing the proactive contamination control program with individual machine goals and system control, necessary in every maintenance program. The final benefit in using this process of filter selection and contamination control is the fact that it can be greatly simplified by using the LEM (Life Extension Method) and the FSC (Filter Selection Chart).

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