

Automatic Transmission Hydraulic System Cleanliness – The Effects of Operating Conditions, Measurement Techniques and High-Efficiency Filters

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ABSTRACT

Malfunction due to solid particle contamination can be separated into two types. Type I malfunctions involve large particles (>150 micron), most often the remnants of manufacturing, and generally lead to early life repairs. Type II contamination includes much smaller particles (<50 micron), most of which are either generated wear debris, or particles ground up from larger Type I debris. These Type II particles are responsible for erratic valve performance, poor cooling and lubrication, and the accelerated degradation of Automatic Transmission Fluid (ATF), all of which promote transmission mid-life failures. This paper focuses on Type II contamination only.

Hydraulic system cleanliness has a significant impact on shift timing, feel and general transmission durability. In order to manage the system cleanliness, a uniform repeatable measurement system must be available. Further, the effects of operating conditions must be known and considered. Once operating effects are accounted for, and reliable measurement techniques can be applied, improvements in system cleanliness may be developed and evaluated in a methodical manner.

Using ultra-high efficiency ($E_x = 99.96\%$) bypass micro filters dramatically reduces the contamination level of solid particles in the ATF. Intensive road tests with and without the additional application of such filters are compared. On average, the ATF cleanliness level was measured to be 4–5 points lower on the ISO 4406 standard scale when using NTZ filters. This is equivalent to a reduction by a factor of 16–32 in the number of solid particles responsible for Type II malfunctions.

INTRODUCTION

Industrial, aerospace and off-highway equipment manufacturers have long understood the importance of

maintaining hydraulic system cleanliness. Considerable investigation has led to the development and validation of numerous standards applicable to components, systems and measurement techniques. Many of these prior developments have recently been applied to automotive automatic transmission systems, as part of a “Transmission Extended Life Initiative”.

The automatic transmission hydraulic system is responsible for :

- Gearbox lubrication and cooling,
- Shift actuator power supply,
- Hydraulic control system logic (hydro-mechanical and electro-hydraulic valves; the solid-state electronic subsystem is recognized, but not included here)
- Fluid transfer (fill the torque converter).

In the quest for improved vehicle performance and fuel economy, two- and three-speed open converter automatics have been replaced by four-, and five-speed units (six-speeds are on the horizon), all with locking torque converters. Acceleration from a standing start to cruising speed now involves as many as eight “shift events” (including converter unlock/re-lock). Events that are harsh or dragged out, delayed or “piled-up”, shift business, hunting, etc., all contribute to negative shift presence and lead to “Things Gone Wrong” (TGW). ATF contamination is the major contributor to hydraulic valves that exhibit poor regulation, delayed response (Figure 1) or total malfunction – TGW.

Consumer studies from multiple researchers (e.g. “Consumer Reports”, JD Power, etc.) have repeatedly listed ‘reliability’ and ‘durability’, as leading customer wants, and that customers perceive variability as an indicator of “Not Quality”¹. The customer senses this variability when poor regulating valve performance results in command pressure errors at ratio change actuators (clutch or band cylinders); Shifts become harsh

EFFECTS OF OPERATING CONDITIONS

As illustrated in Figures 3 and 4, the system cleanliness is dynamic. The complexity of transmission hydraulic systems (many have in excess of 20 valves, often housed in die cast bodies comprised of a labyrinth of passages), the debris generation characteristics of gearboxes with wet friction elements, and remnant debris from manufacturing provide a rich load of solid particles with abundant locations in which to settle. Transient events such as up-shifts, disturb these settled particles and raise their concentration in the circulating ATF. Note how the cleanliness levels are quasi stable during the “Suburban Cycle”, often at or near the maximum concentration developed under stress (See Figure 3). This contrasts with the asymptotic decrease in concentration during steady-state “Interstate Cruise” runs.

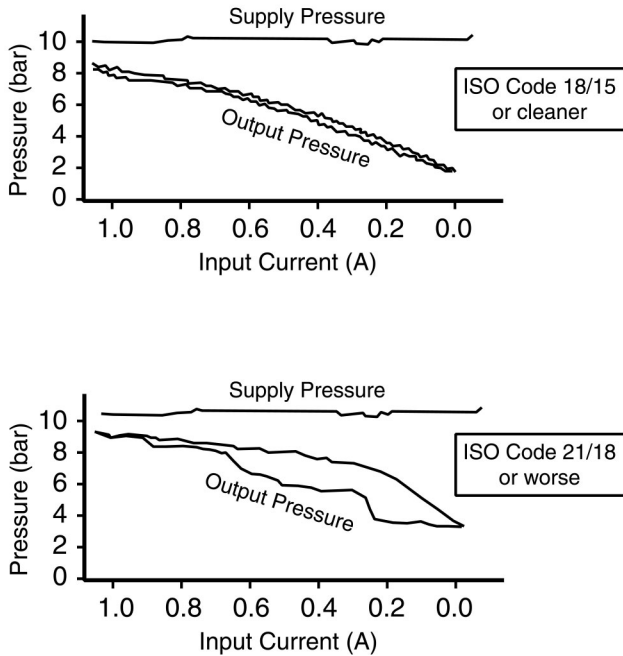


Figure 1 — Typical electro-hydraulic valve degradation hysteresis growth due to contamination.

or dragged out. While current adaptive control algorithms may correct subsequent shifts, clutch and band distress has occurred, and friction element life has been reduced. Contaminated lubrication has a significant effect on bearings². Circulating copper and iron wear debris are oxidation catalysts and accelerate ATF breakdown, resulting in reduced cooling and poor lubrication³.

MEASUREMENT SYSTEM

The measurements reported in this paper are in accordance with SAE J 1165⁴ (based on ISO 4406, Revised 1987) and are given as an index in the form of a number pair, e.g. 18/15. (Note: The ISO has recently upgraded 4406 with major revisions to the calibration of particle counters, and has redefined the index to include a three-number indicator. Since the experiments discussed here commenced prior to these revisions, and because the equipment used was calibrated per the preceding standards, all references within this paper are in accordance with ISO 4406-1987). Table 1 shows the ISO cleanliness codes from 1 to 28, covering particulate counts from 0.01 to 2,500,000 particles per milliliter of sample. The first digit indicates the particle count above 5 microns; the second digit indicates the particle count above 15 microns. For example, an ISO measurement of 14/12 (in the two-digit system) indicates that the oil contains between 80–160 particles/ml larger than 5 microns, and between 20–40 particles/ml larger than 15 microns in size.

ISO Code Range Number	Minimum Particles / ml	Maximum Particles / ml
1	0.01	0.02
2	0.02	0.04
3	0.04	0.08
4	0.08	0.16
5	0.16	0.32
6	0.32	0.64
7	0.64	1.3
8	1.3	2.5
9	2.5	5
10	5	10
11	10	20
12	20	40
13	40	80
14	80	160
15	160	320
16	320	640
17	640	1,300
18	1,300	2,500
19	2,500	5,000
20	5,000	10,000
21	10,000	20,000
22	20,000	40,000
23	40,000	80,000
24	80,000	160,000
25	160,000	320,000
26	320,000	640,000
27	640,000	1,300,000
28	1,300,000	2,500,000

Table 1 — ISO cleanliness codes, range numbers and concentrations bands.

Comparison - Benchmarked Automatics Fluid Cleanliness

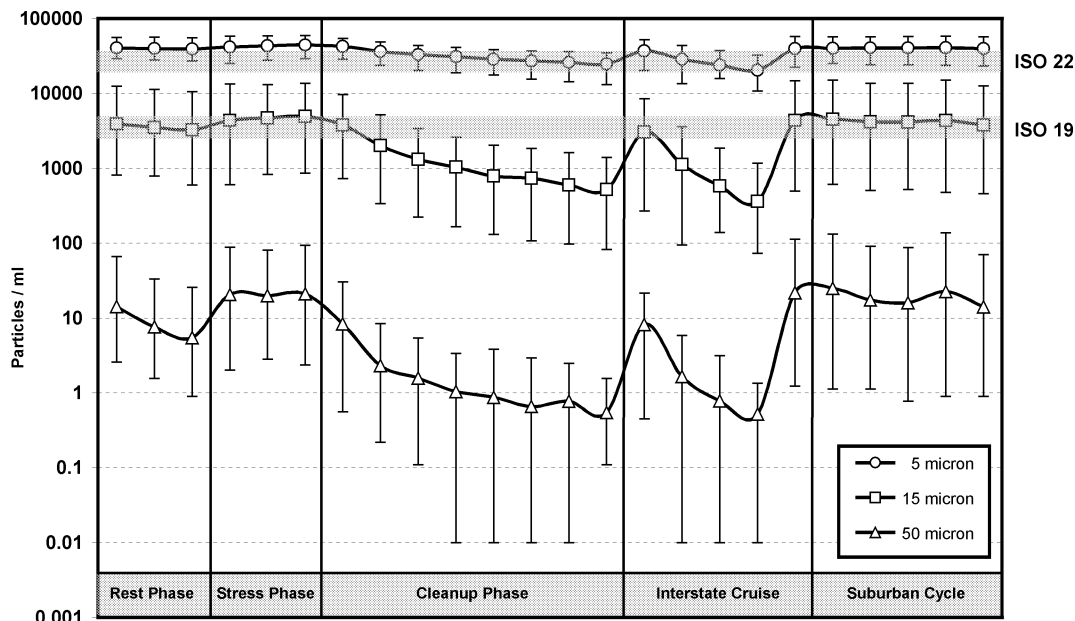


Figure 3 — Benchmarked automatics fluid cleanliness. Measured values for eight different transmissions from four different manufacturers are averaged (symbols and solid line), and the range of individual values is indicated (vertical bars). On average, ISO 4406 cleanliness index was 22/19.

TEST PROCEDURE

Prior methods used to assess ATF cleanliness relied heavily on bottle sampling techniques. These procedures proved cumbersome, time consuming, and required careful attention to procedural details to achieve meaningful results.^{5,6,7} Since the total ATF charge cleanliness was inferred from the cleanliness of the sample bottle, minor errors in sampling technique, cleanliness of the bottle, or preparation of the sample immediately preceding the analysis could all produce errors. Furthermore, the effects of operating condition could not be evaluated because the bottle could only be filled under static conditions. A more reliable, repeatable, robust and dynamic method was needed.

“On-line” sampling involves the use of an automatic particle counter, plumbed into a functioning hydraulic system. It permits real-time monitoring during transient operation, and requires no preparation or handling of sample bottles. All the fluid sampled is returned directly to the system under test, without loss of fluid. The sample analysis is completed in minutes, and recorded on hardcopy and in an electronic buffer. Presently, there are over six models of portable automatic particle counters,^{7,8} most of which employ

“light blocking” transducers to measure the size and count the number of solid particles suspended in the circulating fluid. We selected the UCC CM-20 monitor for this effort, because of its high saturation level,^{7,8} and rugged portability. Additionally, since the fluid monitor sampled fluid under pressure (typically 4–8 Bar), undissolved air was forced into solution, thereby eliminating the need for “de-gassing” prior to sampling⁷ – a further simplification. It must be noted, however, that excessive amounts of aeration (greater than 10% by volume) may produce erroneous readings. These are represented by a sudden increase in large particle (>100 micron) concentrations, with no similar increase in smaller particle (<50 micron) concentrations. It must be recognized by the reader that high levels of undissolved air indicate serious hydraulic system deficiencies over and above that of solid particle contamination.

The availability of small, portable automatic particle counters permitted the measurement of ATF cleanliness “real time”, during most any operating condition. Application of this tool allowed the development of a series of dynamic tests to establish typical cleanliness levels, and the true effect of changes to the filtration system.

STRESS TEST — This test procedure involved three distinct phases: the “Rest Phase”, “Stress Phase”, and “Clean-Up Phase”. Due to the aggressive shift maneuvers, this procedure required a closed course test track. Vehicle preparation included installation of the automatic particle counter (Figure 2) and a four hour dormant period preceding the test. Immediately after starting the engine, the particle counter was initiated, system function verified, and the first sample was taken. Two additional samples were collected in rapid succession. These first three samples established the “at rest” cleanliness level. The vehicle was then driven onto the test track and a series of up-shifts and down-shifts were executed. The test runs included light throttle acceleration through top gear, braking to dead stop (automatic downshifts), moderate throttle acceleration, braking to dead stop, wide-open throttle acceleration to safe maximum speed and gear range, braking and manual downshift to dead stop, the cycle being completed with a reverse engagement. The cycle was continuously repeated while three samples were taken in rapid succession. Upon completion of the “Stress Phase”, direct drive was selected, and the vehicle was driven at a steady throttle position (near-constant vehicle speed) with minimum disturbance to the hydraulic system. The intent was to make no ratio changes or converter clutch state changes (converter clutch remained locked). Eight samples were collected during this Cleanup Phase (See Figure 3).

INTERSTATE CRUISE CYCLE – To further characterize the effects of operating condition, a test procedure was developed to monitor ATF cleanliness during high-speed (120 km/h) steady-state operation. The vehicle was prepared as in the “Stress Test”, with a prescribed route on a selected public road defined. This route was chosen to provide minimum variation in transmission loading and thus required few grades, none of which would force a downshift, and constant speed limits throughout the route. Furthermore, traffic conditions were selected

which permitted travel at a near-steady speed. The particle counter was initiated upon entering the interstate highway, and the first sample was taken at t=0. Three more samples were taken at 10 min intervals. The vehicle then exited the limited access road as soon as practical, and a series of moderate throttle up-shifts was completed. After a further 10 minutes, a final sample was taken. This test demonstrated the effects of steady-state operation and is illustrated in Figure 3 as well.

SUBURBAN CYCLE – Additional ATF cleanliness characterization was needed to represent suburban use. Like the “Interstate Cruise Cycle”, this test was conducted on public roads, over a prescribed route. This route was selected to insure that multiple shifts were completed, with no extended idle periods – the vehicle was moving most all the time. Traffic conditions were selected to force repeated startup and speed changes. As before, the particle counter was initiated and a first sample was taken upon entering the public road, with subsequent samples taken at 10 minute intervals. Again, a total of five samples were collected. ATF cleanliness during this cycle is also illustrated in Figure 3.

CORRELATION STUDIES – These test procedures were developed and evaluated at The Ford ATEO Labs, and were validated for use there over a period of four years. Correlation studies with multiple vehicles demonstrated repeatability of one ISO code or better for any given operating point in the various cycles. Continuous monitoring during daily driving demonstrated that this test procedure captured the extremes of operating cleanliness, *i.e.*, no public road operating condition developed levels as high as the “Stress Phase” or the “Suburban Cycle”, and none lower than the “Clean-Up Phase.”

Further effort with various filtration systems (external high-efficiency full-flow filters, ultra-high efficiency bypass filters, improved-efficiency intake filters, etc.) demonstrated that these procedures could

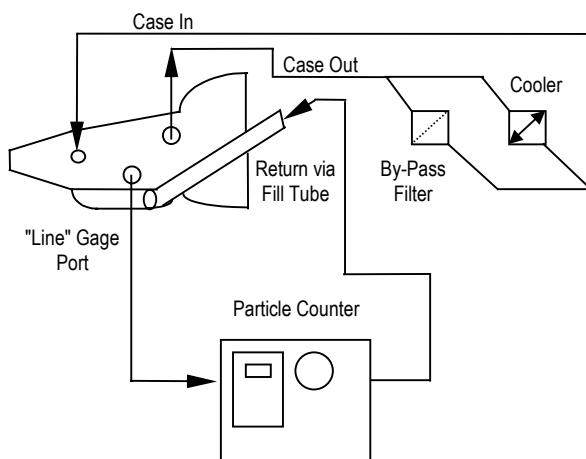


Figure 2 — Particle counter installation schematic.

Component	Manufacturer	Required Cleanliness Level
Vane Pump Series V10	Vickers (Eaton)	18/15
Gear Pump Series H	Parker-Hannifin	16/13 (SAE Class 4)
Variable Vane Pump Series PPV	Parker-Hannifin	16/13 (SAE Class 4)
Directional Valve DG4V	Vickers (Eaton)	18/15
Relief Valve, Elec. Prop Series DSA	Vickers (Eaton)	16/13 (SAE Class 4)
Servo Valve Series ST	Parker-Hannifin	15/12 (SAE Class 3)

Table 2 — Required cleanliness levels for catalogued components.

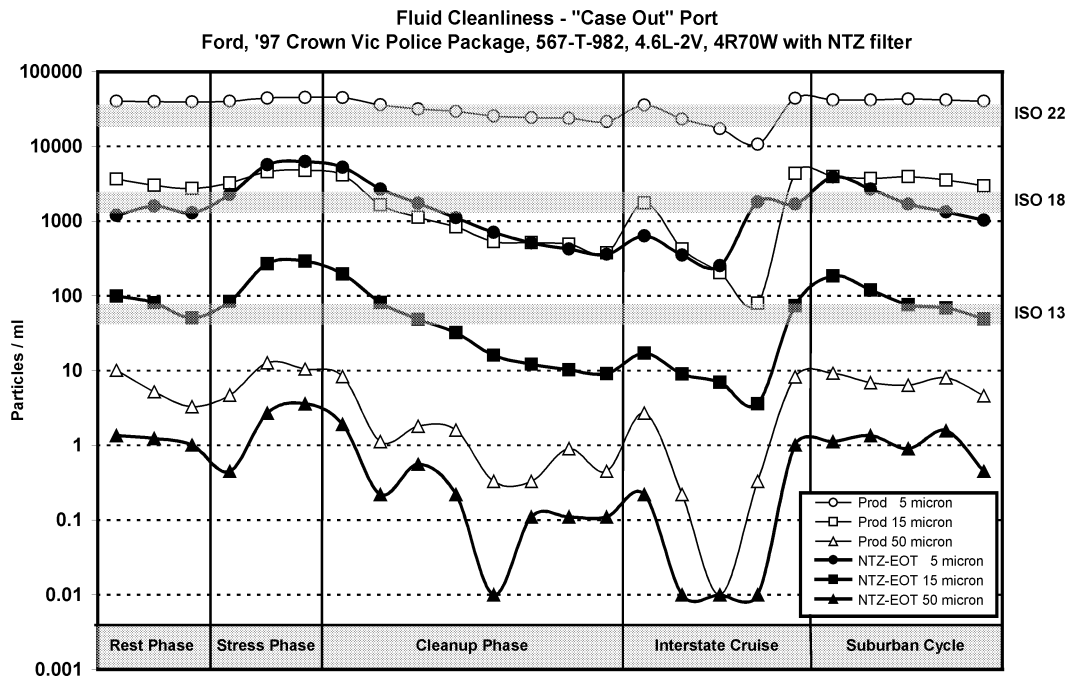


Figure 4 — Transmission fluid cleanliness comparison. A Ford '97 Crown Vic Police Package was subjected to the tests described in the text. Open symbols represent measurements of fluid cleanliness for a standard transmission system with no extra filtration. The average ISO code is 22/18. Filled symbols and solid lines represent measurements for a transmission system containing an additional NTZ bypass micro filter. The ISO cleanliness code in this case is 18/13.

be effectively used to validate filter supplier claims, evaluate effectiveness of product improvements, and verify the achievement of target operating cleanliness. For proprietary reasons, these data have been omitted from this paper.

BENCHMARK COMPARISONS

Figure 3 illustrates the range of cleanliness found in eight transmission systems, manufactured at six different plants from four different manufactures. It must be understood that these values represent the cleanliness of the circulating ATF, and do not reflect any gravimetric values associated with "as built" cleanliness (Type I Contamination). Furthermore, the data were gathered from single samples, and are thus "typical". All were low-mileage units (less than 5,000 km) and had not been serviced since installation at the vehicle assembly plant. Although no statistical significance is represented with respect to unit-to-unit variation of any given model transmission, it can be seen that the change in cleanliness throughout the operating range is typically an order of magnitude, and in some cases as high as two

orders of magnitude. In fact, all the models investigated exhibited similar behavior throughout the series of tests. All the benchmark units had similar filtration subsystems, *i.e.*, all were equipped with (pump) intake filters only – none had pressure side filtration.

ESTABLISHING THE REQUIRED CLEANLINESS LEVEL

To achieve long life and consistent, reliable hydraulic component performance, contamination must be controlled to acceptable levels known as the "In-Service Cleanliness Level" (ISCL). Early in the transmission design process, the engineer must specify the ISCL and include adequate equipment (filters) at appropriate locations in the hydraulic system. To establish the ISCL, the engineer must understand the impact that circulating contamination has on the various transmission components. Considerable guidance can be found with respect to ISCL for roller bearings², hydraulic valves,^{6,7,9} spline joints, plain bearings,¹⁰ and other transmission components and subsystems. Additional guidance can be obtained through research of like components used in other industries. Table 2 lists

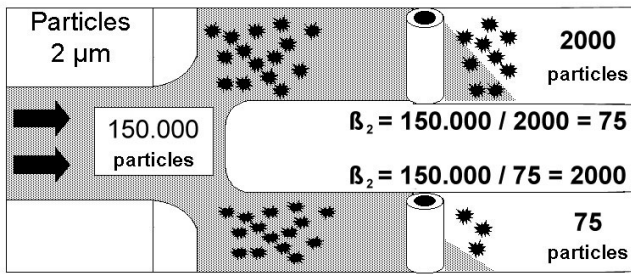


Figure 5 — Schematic diagram illustrating the effect of two different Beta Ratios in a multi-pass test. Even though the Filter Efficiencies differ little more than one percent, the cleanliness levels downstream from the filter differ by more than a factor of 25.

cleanliness requirements¹¹ for industrial components that have similar design parameters and functional requirements as their automotive counterparts.

Test standards and recommended practices have been developed to establish the ISCL above which performance and life degrade, and manufacturer's warranty is voided.^{6,12} While seldomly used in the design of automatic transmissions, commercial/industrial markets, the aerospace industry, and the military use these standards routinely. The ratings established are "market driven" in that components warranted with higher ISCL are viewed by the market place as more robust and are thus preferred. The automotive industry has begun development of transmission-specific "Key Life Test" (KLT) and validation test standards, to be used to establish the required ISCL for future designs.

BETA RATIO AND FILTER EFFICIENCY

The Beta Ratio (β) is a rating system which gives the user an accurate and representative comparison amongst filter media and systems. It is determined by a multi-pass test according to the ISO 4572 standard, which establishes the ratio of the number of upstream particles larger than a specific size to the number of downstream particles larger than a specific size:

$$\beta_x = \frac{Nu}{Nd}$$

Where:

- β_x = Beta Ratio for contaminants larger than X μm
- Nu = Number of particles larger than X μm of volume upstream
- Nd = Number of particles larger than X μm of volume downstream

Figure 5 shows a schematic of this relationship.

The Filter Efficiency for a given particle size (E_x) can be derived directly from the β ratio by the following equation:

$$E_x = \frac{\beta_x - 1}{\beta_x} \times 100$$

Where:

- E_x = Efficiency for contaminants larger than X μm
- β_x = Beta Ratio for contaminants larger than X μm

Table 3 shows a guide to Filter Efficiency.

In view of the very slight difference in efficiency between filters with Beta Ratings of 75 and 2000, a number of authors have suggested that there is little point in specifying Beta Ratings higher than 75. It should be realized, however, that while the Filter Efficiencies may not differ much, the cleanliness levels downstream from the filter differ significantly. For example, a Beta Rating of 75 implies that of 150,000 particles larger than the specified size entering the filter, 2000 will pass through. But with a Beta Rating of 2000, only 75 particles will pass under the same conditions. Thus, while the corresponding Filter Efficiencies only differ by little more than one percent, the cleanliness levels downstream from the filter differ by more than a factor of 25 (see Figure 5).

THE CONTAMINATION PROCESS

Figure 6 shows a model of the oil contamination process in terms of two coupled balances – one representing the contamination level control, the other the effect of the contamination level on component and

Beta Ratio	Filter Efficiency	Particles after Filtration
1	0.00%	1,000,000
2	50.00%	500,000
10	90.00%	100,000
20	95.00%	50,000
50	98.00%	20,000
75	98.67%	13,333
100	99.00%	10,000
200	99.50%	5,000
1000	99.90%	1000
2000	99.95%	500

Table 3 — Number of particles as a function of Beta Ratio (β_x) and Filter Efficiency (E_x).

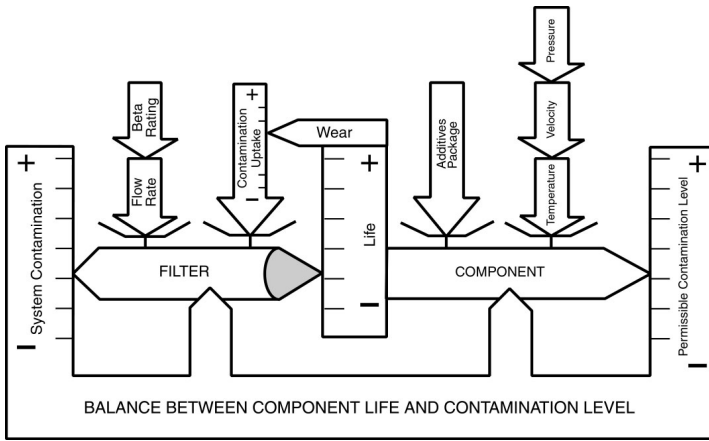


Figure 6 — Balance between the system contamination level and the contamination sensitivity of a component in the maintenance of the desired component life.

system life. This model can provide some useful insights. For example, if the rate of uptake of contamination exceeds the system’s capacity to remove it, the contamination level will rise continuously. Similarly, if the lubricating (protective) properties of the oil are not sufficient to compensate for the contaminant sensitivity of a component, that contaminant sensitivity will limit the permissible load or the oil contamination level needed to guarantee a sufficiently long life.

Only recently, real insight was obtained into the relationship between contamination uptake rate and the lifetime of components. Measures to improve the lifetime of the components (e.g., by using anti-wear additives, or by reducing the pressure or temperature) will reduce wear, and hence the generation of wear particles (debris). This causes the contamination uptake rate to fall, which reduces the load on the filter due to contamination uptake. Reducing the contamination level of the system will extend the life of the components, or at least reduce component wear.

This feed-forward effect is incorporated in Figure 6 by the ‘wear’ arrow on the component balance, which modifies the load on the filter due to contamination uptake. This feed-forward effect has clearly been observed in connection with the use of the NTZ ultra-high efficiency bypass filter with its high Beta Rating and cellulose (fiber) filter medium. The improvement in the cleanliness level of the system when using these filters ultimately reduces component wear to such a low levels that contamination uptake is also drastically reduced. Even though the flow rate through the bypass systems is relatively low, the contamination level can be reduced down to ISO 12/9 in a mobile installation.

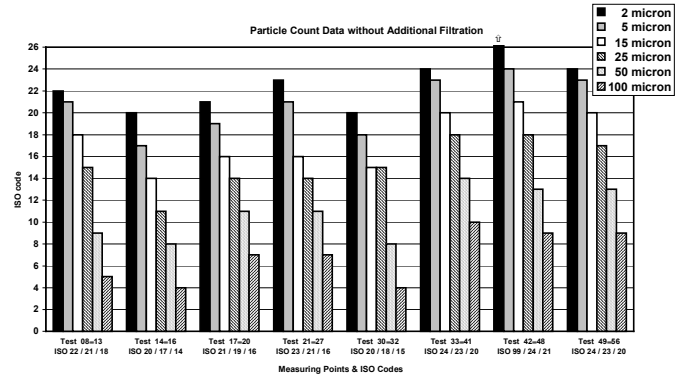


Figure 7 — Particle count data without additional filtration.

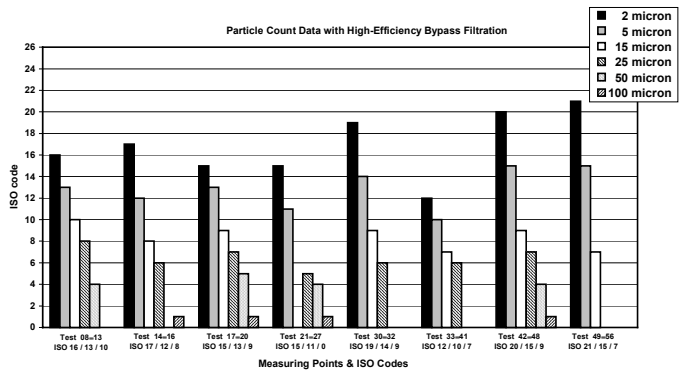


Figure 8 — Particle count data with additional NTZ bypass micro filtration.

THE IMPORTANCE OF FILTERING OUT DEBRIS

Component wear is directly related to the cleanliness level of the system (the cleaner the fluid, the less wear) i.e., to the number of solid particles in the oil. Not only large particles (with diameters roughly equal to the leakage gap width), but also sludge particles smaller than five micron can cause great damage and break downs, and generally degrade the oil. Metallic particles, insoluble oil degradation products, and additive breakdown residues all catalyze the breakdown processes and increase component wear. Table 4 lists the catalytic effect of various metals on the aging process of the oil. The importance of removing even the smallest particles to extend the operating life of oil and components, has been well established.

HIGH-EFFICIENCY RADIAL MICRO FILTRATION VS. CONVENTIONAL TRANSMISSION FLUID FILTRATION

Based on thousands of analyses of transmission oil samples carried out by Fluid Technologies Inc., Figure 7 shows particle count data from 28 transmission oil samples which represent steady-state operating

levels. Cleanliness codes are given according to ISO 4406 (see Table 1).

Because in-line filtration (both suction and pressure-side full-flow) must guarantee a restriction-free flow of the oil to the system, it is inevitable that such filtration systems are limited in their filter fineness. Ultra high-efficiency filtration can only be achieved through a bypass configuration, using just a small fraction of the system flow. Figure 9 shows a schematic diagram of a bypass installation. In a conventional filtration system, the flow through the filter is at least equal to the output of the system pump. But in bypass systems, the flow rate is set to about 10% of the total system volume per hour. It would appear that such a bypass filtration system fails to remove contaminants taken up by the system fluid as soon as they appear. However, numerous automatic transmission systems using NTZ filtration have proven to keep the system fluid at a cleanliness level of ISO 16/9, 15/9 or even 13/8. Figure 8 shows the effect of NTZ ultra high-efficiency on various transmissions. Clearly, these systems have much lower contamination uptake than typically found in automatic transmission systems with only filtration in the main flow line (Figure 7).

Despite the improved quality of modern seals (in particular, their ability to keep contamination out of the system), and a growing recognition for the need to prevent contaminated air to enter the system, the low ISO cleanliness level codes produced by NTZ filtration have made it clear that the majority of the contamination in a modern automatic transmission system is generated by the wear of the system components.

The NTZ filtration system has a Beta Ratio of $\beta_2 = 2470$ and a Filter Efficiency $E_x = 99.96\%$. The filter elements consist of radially-wound highly-compressed cellulose fibers. The polar properties of these cellulose fibers are extremely effective, even for very small particles (down to less than one micron in size), which play an important role in the chemical breakdown of the transmission oil, as shown in Table 4. The high polarity of the NTZ filter minimizes the concentration of these small particles, reducing wear to such an extent that contamination uptake can be dealt with adequately by a flow rate through the bypass filter of no more than about 10 percent of that in the main flow line. Once the oil has been thoroughly cleaned, this type of filter practically eliminates wear due to contaminant particles.

CONCLUSIONS

As automatic transmissions continue to evolve, industry-wide trends are driving the need for cleaner ATF. Customer demands for improved performance and reduced operating cost have resulted in the application of electro-hydraulic valves, “Long Life” and “Fill For Life” ATF, higher internal speeds, reduced package envelopes, fluid charge volumes, and reduced drain intervals. These design and service actions place demands on the fluid, especially with respect to

Catalyst	Water	Total Acid Number	Lifetime Oil (operating hrs)
none	no	0.17	> 3500
none	yes	0.90	> 3500
Iron	no	0.96	> 3500
Iron	yes	8.10	400
Copper	no	0.89	3000
Copper	yes	11.20	100

Table 4 — The catalytic effect of various metals on the aging of mineral oil.

cleanliness. While the market has responded with myriad filtration products, the industry needs to develop uniform, effective, repeatable test methods and metrics to quickly, fairly, and consistently evaluate these components, and establish the total system effect under operating conditions representative of customer use. Bench tests are not enough. The authors have petitioned the SAE Automatic Transmission and Transaxle Sub Committee (SAE ATTSC) for just such an effort.

The experiments discussed in this paper demonstrate the significant impact which operating conditions have on ATF cleanliness. The availability of small, rugged, portable particle counters permit convenient assessment of fluid cleanliness, even during transients. Application of these new tools makes the development of industry standard tests practicable.

Early fluid degradation due to catalytic reactions caused by particles $< 2 \mu\text{m}$ (debris), and accelerated component wear result from fluid which has become contaminated beyond acceptable levels. Once the ISCL is exceeded, hydraulic system variability will initially result in customer perception of “Not Quality,” and, if not corrected, will likely lead to transmission malfunction – the customer is dissatisfied. The design engineer must recognize the systemic impact solid particle contamination has on the transmission, establish the ISCL, and integrate into the system effective equipment (ultra-high efficiency filters) to achieve and maintain the ISCL.

Bypass filtration allows the use of ultra-high efficiency filters. Field tests with NTZ micro filters, which have a $\beta_2 > 2000$ and a Filter Efficiency of 99.96%, have proven to keep the small-particle contamination of ATFs several orders of magnitude below the values measured for conventional automatic transmission systems, and required for modern automatic transmission systems.

Ongoing fleet test, DOEs, and dyno tests within Ford Motor company have demonstrated bypass filtration to be an effective method to achieve improved ATF cleanliness without concern for loss of cooling system capacity. Fleet Vehicles in severe duty have completed in excess of 100,000 km without service and no loss or degradation in transmission performance. While results to date have been most encouraging, further work

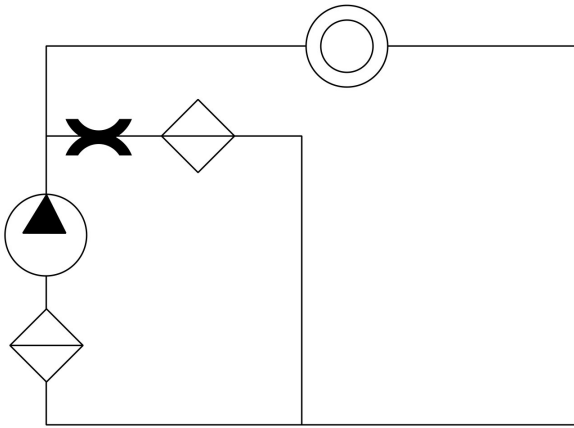


Figure 9 — Schematic bypass filter installation

remains. Future investigation may study the effects on ATF additive package, evaluate reduced wear with lower cost components, e.g., plain bearings in lieu of roller elements, or increased life of current parts – The cleanliness dividend.

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