Paper No. IFC09-018

Fuel Filtration Reality Check

Philip Johnson
Donaldson Company, Inc.

ABSTRACT

Fuel filter manufacturers once enjoyed a relatively simple life. The fuels we filtered were typically refined from oil and were made to carefully-controlled standards to meet engine performance characteristics. Engine designs were based either on the Otto or Diesel cycle, and they in turn were primarily designed to meet appropriate field operational requirements.

In the last twenty years, engine design and the types of fuels available have changed significantly. These recent changes have been increasingly driven by legislation, regulation, and a rapidly escalating oil price. Changes to engines are occurring at an exponential rate, unprecedented in the past history of the internal combustion engine.

Yet fuel specifications and fuel filtration have seen very little change. A clarification of fuel specifications is necessary and will be driven by stakeholders within the fuel filtration and engine manufacturing industries or through further government regulation. The choice is ours, but not for long.

INTRODUCTION

Current fuel filter designs typically address contaminants such as dirt and water. Future fuel filtration will still need to control dirt and water, but will additionally need to handle newer contaminants such as gas entrainment, fuel oxidation and degradation products, a range of different bio-fuels, pipe line additives, lubricity agents, and static electricity. The contaminant list grows daily, outpacing industry's ability to clarify corresponding changes to fuel and filter specifications. The effective design of future fuel filtration will depend upon clear, up-to-date, and relevant specifications. It will also dictate a change in the way fuel filtration is done.

Anticipated Alternative Fuels?

Fuels

On December 19, 2007, the U.S. Congress passed the Energy Independence and Security Act. A large part of this act aimed to save energy through improved design and the introduction of bio-fuels as alternatives for fossil fuels. Only two years ago, the future for ethanol plants seemed secure, and bio-diesel plants looked set to follow a similar path.

However, the current status of these alternative fuels was summarized in a recent Star Tribune column written by H.J Cummins, (**H.J. Cummins**, *Star Tribune*: June 23, 2008). According to Cummins, a series of forces have shoved:

> ethanol's main ingredient—corn—to record high prices that have squeezed, if not erased, industry profits.
>
> It's quashed the ethanol boom of two years ago and left the industry in shambles, with operators postponing building of plants, and even delaying indefinitely the start-up of plants that have recently been completed. A growing chorus of legislators and energy experts in Washington is questioning a new round of federal mandates for ethanol production passed last December and debating suspending them or rolling them back.

Less than a year after the Energy Independence and Security Act was issued in the U.S., there are already signs of descent. Similar reservations are also being raised in Europe, with the specter of rising food prices around the world.

While it's clear the bio-fuel industry is here to stay, there are some major viability issues still to overcome, as well as many technical problems which continue cropping up in the field. These issues raise a serious question for the filtration industry: What fuels should we be planning for, what will the various concoctions be—B2, B5, B10, B20, B100, or combinations of B and E, or perhaps a cocktail of other letters from the alphabet—and what will their specifications be?

Filter/Fuel Compatibility

The filtration industry has long struggled with fuel and filter material compatibility issues. That problem is now being compounded through limited material compatibility test data, especially for many of the new bio-fuels and also for some of the newly refined oil and coal-derived fuels and their additives. With the introduction of ultra low sulfur diesel (ULSD) in the North American market two years ago, filter manufacturers began to experience material compatibility issues.

Some led the filtration industry to believe that the problem occurred because of refinery process changes leading to aromatic compounds along with sulfur being blended into aviation fuels. Others informed the industry that gasket expansion is a consequence of blending more bio-diesel into regular diesel. In laboratory testing we have seen that ethanol fuels rapidly degrade hot melt glues in filters and can react with aluminum components in filter heads. Adverse reactions with other metals and plastics not previously affected by gasoline or diesel are now common. All this begs the same sort of questions posed earlier in this paper: ***What sort of fuel are we currently filtering, and what sort of fuel will we be filtering in the future?***

Need for New Standardized Fuel Specifications

There is a growing need for new and standardized fuel specifications both physical and chemical. In 1998, engine manufacturers embarked upon the Worldwide Fuel Charter as an attempt to set international standards for fuels. The charter states in the preamble for the 2006 edition:

> This edition realigns fuel specifications to more accurately reflect market conditions and engine and vehicle requirements. Advanced ultra-clean engine and vehicle technologies have begun to be introduced in some markets and will continue to be used in increasing numbers. These new technologies require the best quality—as represented in Category 4—to achieve their emissions and performance potential.

Figure 1. Worldwide Fuel Charter[3]

An examination of the Charter reveals that the only guidance the filtration industry gets regarding fuels and their cleanliness requirements is an illustration on page 50 that shows an ISO 4406 particulate cleanliness specification of 18/16/13. This is in recognition of the need for cleaner fuels to be delivered from the distribution channel.

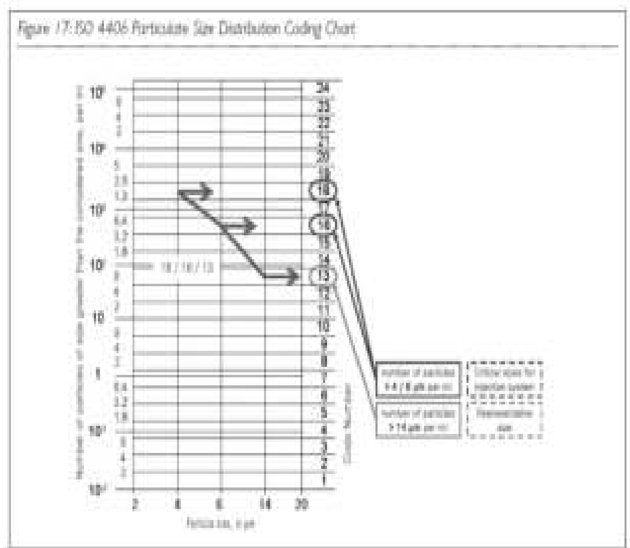


Figure 2. Worldwide Fuel Charter ISO 4406 Fluid Cleanliness Requirement[3]

The rationale behind setting a cleanliness standard was the recognition by engine manufacturers that by 2006 diesel fuel injector systems were already operating above 1600 bar pressures, thus requiring higher cleanliness levels. The standard also recognized that operating pressures were likely to continue to rise for the foreseeable future.

Current cleanliness recommendations by some manufacturers of high pressure fuel injection systems have already indicated they need significantly cleaner fuels. They already require fuel in an ISO 4406 cleanliness range of 12/9/6 or better for on-vehicle filtration.

Several studies have been conducted on fuel cleanliness coming out of the pump, and it's not uncommon to find a newly-delivered batch of diesel fuel with an ISO cleanliness level of 22/21/18. ***So who is signing up to cleaning diesel fuels to cleanliness levels of 12/9/6 or better?***

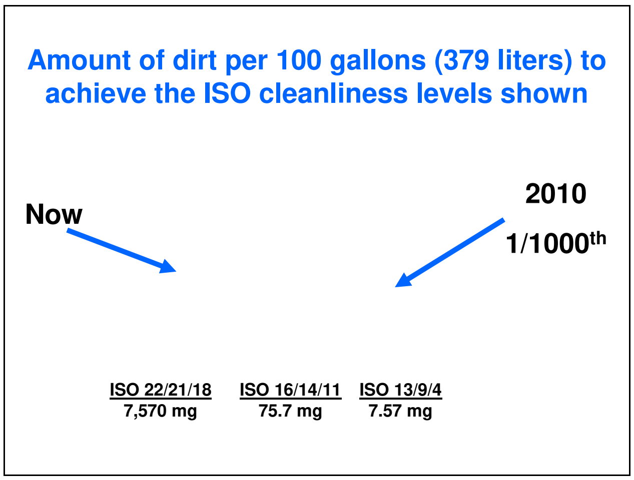


Figure 3. Contamination by ISO Medium Test Dust Required per 100 Gallons of Fuel to Meet Various Cleanliness Levels

Figure 3 shows approximately how much test dust (dirt) is required to contaminate 100 gallons of fuel to an ISO 4406 cleanliness level of 22/21/18, 16/14/11 and 13/9/4. Cleaning fuel from an ISO 4406 cleanliness level of 22/21/18 to approximately 12/9/6 or better requires approximately a one thousand times reduction in the particulate contamination. By the year 2010, this is the sort of cleanliness standard that fuel injection manufacturers will likely be seeking for on vehicle filtration systems. While this is relatively difficult to achieve, it's not an unrealistic objective even using current filtration technology. To get to these cleanliness levels will most likely require high efficiency filtration and possibly multiple filtration cycles.

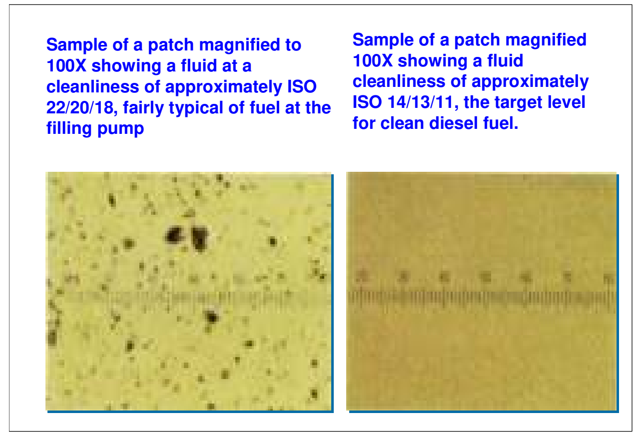


Figure 4. ISO 4406 Contamination Levels 22/21/18 and 14/13/11

Figure 4 shows two membranes coated with contamination. The one on the right is a target level for clean diesel before it goes into a vehicle fuel tank.

Where and how should the filtration be applied to achieve an ISO 4406 cleanliness level of 12/9/6 for a diesel injector pump*?* This question raises some thorny questions as to who should be responsible for the cleanliness. There are some practical issues to review first. With current filtration technology, most fuel filtration on vehicles is done with pleated cartridges containing some form of depth filter media.

Figure 5. A Typical Suction Fuel Filter Water Separator for Class 8 Truck Applications

A cartridge of the type depicted in Figure 5 typically can capture between 100gms to 200 grams of ISO Fine Test dust, depending on the efficiency of the media. If we consider a vehicle with a fuel consumption rate of 100 gallons per day receiving daily deliveries of fuel at an ISO 4406 cleanliness level of 22/21/18, it's theoretically possible that conventional filters would last 15 to 20 days and meet contamination levels set by Worldwide Fuel Charter of 18/16/13–still well short of actually meeting the needs of Fuel Injection Manufacturers cleanliness requirements.

In reality, new fuel injection systems will likely require much higher cleanliness levels (ISO 4406 of 12/9/6 (Ref1)). Vehicle filters required to meet this standard may need to be significantly higher in efficiency - certainly better than 4 µm absolute. Filters will need the ability to remove significant quantities of solid particulates below 4 µm in size. Traditional 4 µm filtration capable of doing this generally has a much lower dirt holding capacity. This might imply that the same-sized element shown in Figure 5 which could capture and retain all the dirt, might last as little as 5 to 10 days in operation with a very high efficiency media. Neither 5-10 days nor 20 days operation are considered acceptable to engine manufacturers nor engine operators. A likely future scenario is that bulk pre-filtration will be required. Before drawing this conclusion, there are other questions that require answers.

An obvious question is, given that diesel engines have operated satisfactorily for many years without changing filter elements every few weeks, what has changed—and how did they work in the past?

Questions Begging Answers

An unfortunate characteristic of most depth filters used on vehicles is that with fluctuating flow and vibrations they have a tendency to decline in performance. This can be significant in terms of retention of contaminant during operation.

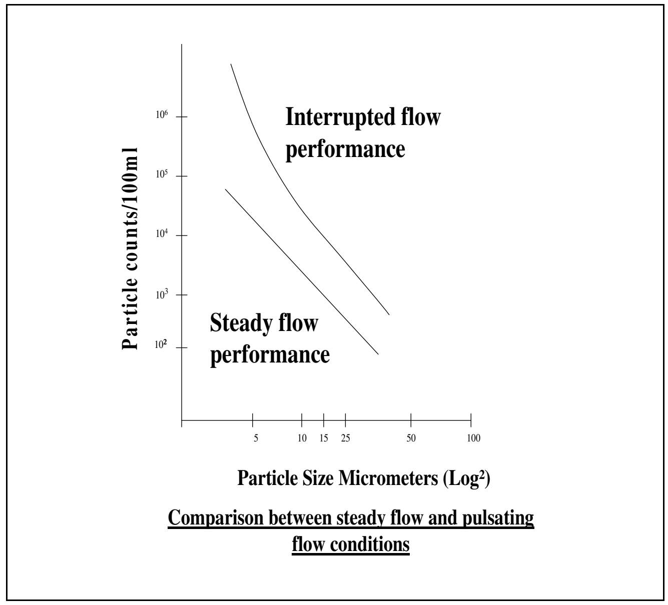


Figure 6. Comparison of a Variation of Particle Size Retention of a Filter Media, Down Stream of the Media, when Subjected to Interrupted Flow[2]

Figure 6 shows the relative difference between steady state flow and interrupted flow of a typical filter media. Figures 7 and 8 below depict work done at Southwest Research Institute® (SwRI®) investigating diesel fuel injector system wear, caused by particulate contamination.

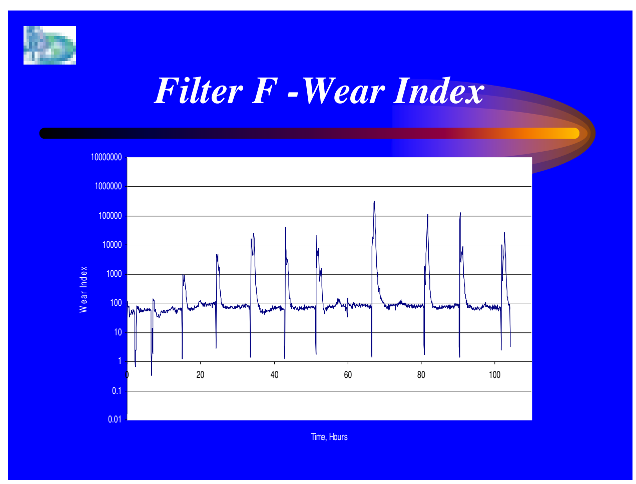


Figure 7. Shows a Wear Index against Time in Hours[5]

Figure 7 shows the affect on wear by starting and stopping the system during testing. The conclusion that can be drawn from these tests is that interrupted flow can significantly affect wear.

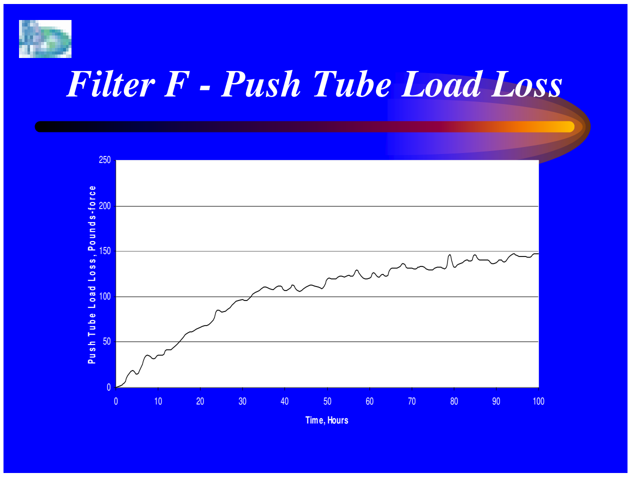


Figure 8. Shows Push Tube Pressure Loss in Pounds Force against Time in Hours[5]

Size comparison ACFTD & NIST

ACFTD Calibrated Size (μm) of : (ISO 4402)	Corresponds to a NIST Calibrated size (μm (c) of: (ISO11171)
0.8	4
1	4.2
2	4.6
2.7	5
3	5.1
4.3	6
5	6.4
7	7.7
10	9.8
12	11.3
15	13.6
15.5	14
20	17.5
25	21.2
30	24.9
40	31.7

Figure 9. Comparison of AC Fine Test Dust when Calibrated by the National Institute of Science and Technology (NIST)

This same test at SwRI also concluded that the push tube load loss was significantly less with high efficiency filtration when compared to standard efficiency filters. The comparison was markedly different between filters that had a high efficiency at 4μm compared to 10 μm filters.

Depending on how the data is viewed, another conclusion that can be drawn is that contaminant migration may well be the only way of ensuring that the filters can last a reasonable length of time in operation!

If we assume that dirt migration extends filter life, how clean should fuels be, and how should we filter them?

To answer this question, we need to look back into some history of filtration testing before drawing conclusions.

One of the standard test dusts used by the filtration industry for many years for fuel and oil testing was AC Fine Test dust. This finely ground dust ceased to be available in the early 1990s, and a new test dust standard was required for filter calibration. Today most fuel and oil filtration testing is typically conducted using a range of ISO-calibrated test dusts.

As part of the introduction of these new calibrated test dusts, it was necessary to compare them with their predecessor standards, AC test dusts.

What was found by the NIST in the recalibration exercise was that particles of AC fine test dust thought to be below 4 μm were typically larger and that particles over 14 μm were slightly smaller. Figure 9 shows a comparison of the data.

This realization of particle sizing raises some fundamental questions as to how we should attempt to filter fine particulates below 5 μm in size.

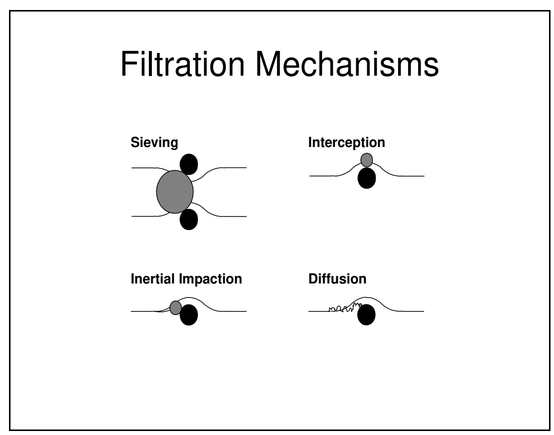


Figure 10. Filtration Mechanisms

Traditional filtration theory suggests that there are two primary mechanisms involved in depth media filtration of liquids, namely sieving and interception.

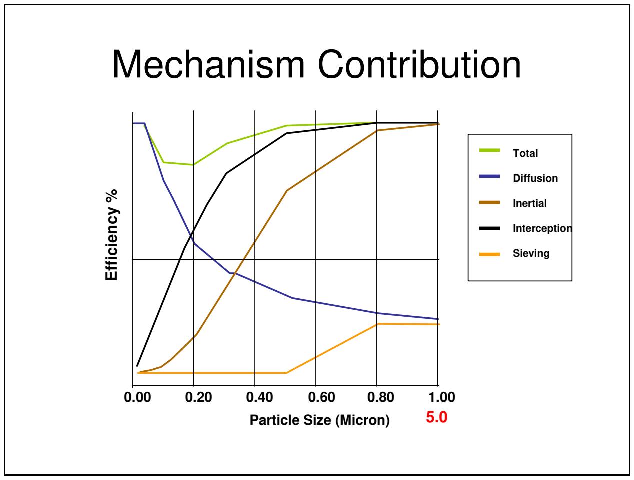


Figure 11. Contribution of Filtration Mechanisms in Air

From previous filtration theory, it was thought that the primary contributor for filtration down to 1µm or 2µm in size was sieving. While sieving still remains a major filtration factor in air and liquids, it's become more obvious that interception has a larger contribution to fine particulate capture below 5 µm in liquids than was previously thought. What we consider 1 µm in Figure 10 may actually closer to 3µm -5µm in reality for liquids. The model shows that sieving has a rather minimal contribution to initial filtration at this size range.

The filtration model shown in Figure 11 also fails us in that it doesn't tell the full story once a dust cake forms within a filter; it looks only at the initial filtration characteristics.

What size particles cause wear?

Rolling wear and abrasive wear are two common forms of wear caused by hard particulate contamination. Figure 12 depicts a graph from a 1982 paper titled "Influences of Wear Debris on Rolling Contact Fatigue" by R. S. Sayles and P.B. Macpherson. In essence, they determined that relative rolling contact bearing life could be significantly increased by adding finer and finer filtration and by excluding dirt particles above certain sizes. The blue line of the graph approximates their work. The green line on the graph is an approximation of what the filtration efficiency might have been if the filters they had been using back in 1982 had been tested using modern particle counters and ISO Medium Test Dust, rather than AC Fine Test, the test dust of the day.

What the green line would imply is that filtration that excludes 5µm and larger hard dirt particles would lead to a significant increase in bearing life. If hard particles close to or larger than the dynamic clearance of the oil film thickness of the bearing can be excluded, bearing life is significantly extended.

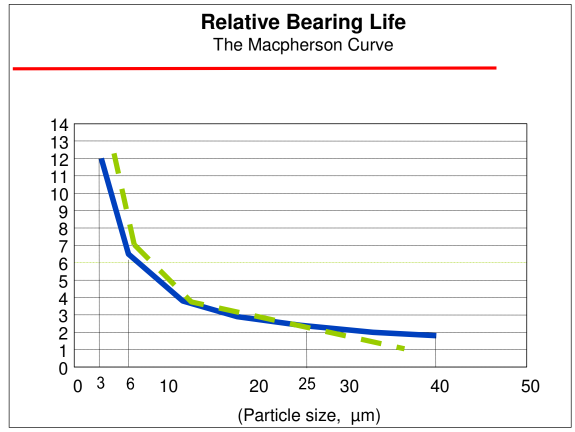


Figure 12. Macpherson Curve with Super-Imposed Line Depicted in Green Showing Estimated Size Distribution if Filters had been Tested Using NIST-Calibrated ISO Test Dust[6]

For the last thirty to forty years, most filtration design for fuels and oils has focused on achieving this result and has successfully used a combination of sieving and interception in media design.

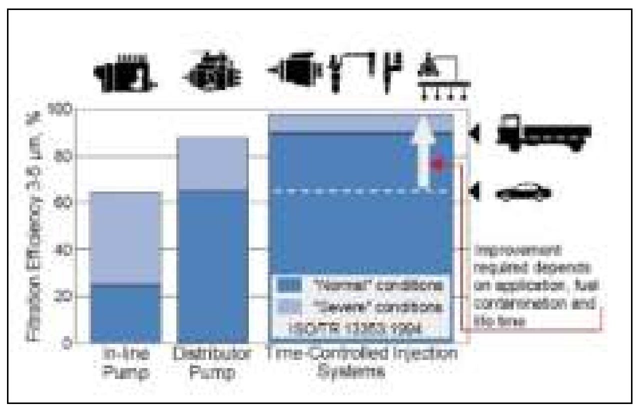


Figure 13. Projection of Fuel Filtration Requirements Based on Changing Injector Design by Robert Bosch GmbH[4]

In order to develop new high pressure fuel rail injection systems, machine tolerances have had to become much tighter and more controlled (Figure 13). These changes necessitate better lubrication and finer filtration; filtration probably well below 5 µm will now be required. The needed changes will likely require the development of new filtration approaches relying on combinations of filtration and system design and perhaps utilizing interception much more as a primary filtration mechanism.

What sort of filtration is required to filter fine particulates from Fuels?

One obstacle to answering this question is having a reliable test and suitable instrumentation that can measure particulate sizes below 4 µm with a reasonable level of consistency and accuracy.

Currently, there are two typical approaches to cleaning fuels and oils. One approach is to dilute the contamination by passing the fluid through a filter multiple times to gradually reduce the concentration of the contaminant. The other is to use a high efficiency filter and remove the contamination in a single pass.

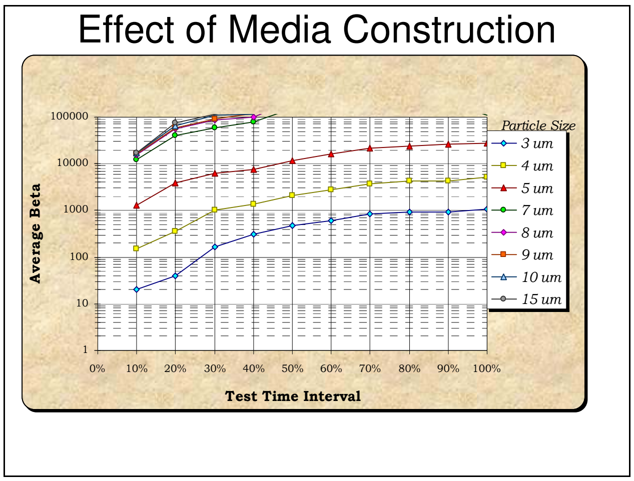


Figure 14. Shows How Efficiency Increases as a Dust Cake Forms Over Time During a Multi Pass Filter Efficiency Test

Figure 14 shows the efficiency of a filter media at collecting dirt particles across a range of particle sizes. The media was tested in a multi-pass configuration. If we focus on the blue, yellow, and red lines, it shows how the efficiency of the media changes over time at capturing particles less than 5 µm in size. It can be seen that the initial efficiency starts off low and gradually increases throughout the test as the filter loads up with contaminant.

While this type of media would most likely achieve very high cleanliness levels in a closed circulating system such as that used in typical hydraulic or engine oil filters, it would likely not be appropriate for use as a high efficiency on vehicle diesel fuel filter media because of its low initial efficiency.

In contrast, Figure 15 shows a media more suitable for high initial efficiency diesel filtration. It starts with a high initial efficiency and maintains high efficiencies throughout its life.

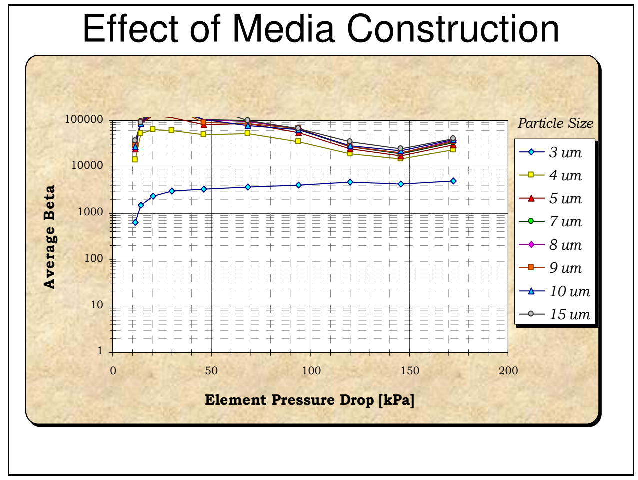


Figure 15. Shows a High Initial Efficiency Filter Media Designed to Remove Fine Particulates from Installation

What is not shown in either Figure 14 or Figure 15 is the dirt holding capacity and how this would translate into filter life.

How does the size of contaminant affect filtration?

Figure 16 highlights the need to understand what type and size of contamination is typical in field applications.

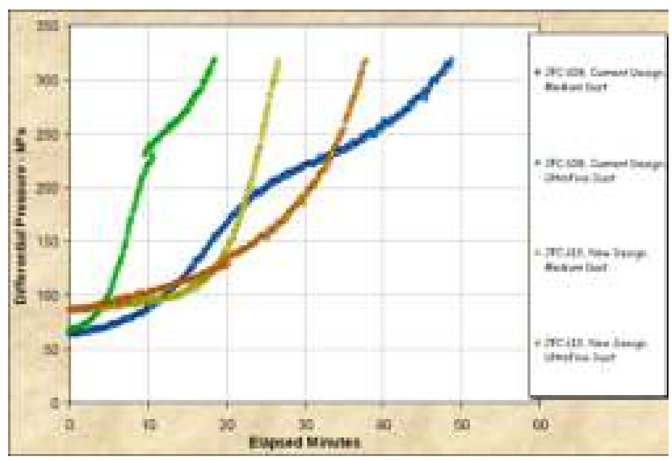
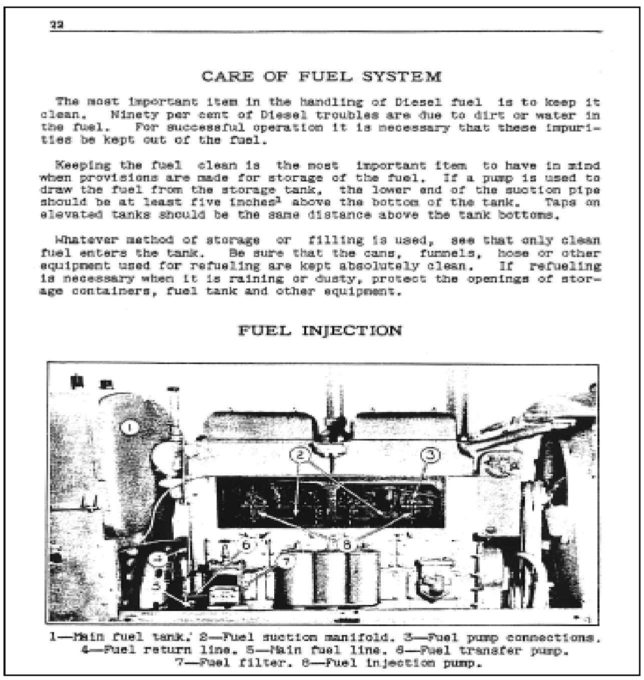


Figure 16. Shows the Experimental Life of Two Grades of Filter Media with Similar Efficiencies, When Tested with ISO Ultra-Fine and ISO Medium Test Dust

In Figure 16, the blue line showed a very promising media for Jet A fuels and ULSD when tested using ISO medium test dust. However, when the exact same test was run using ISO ultra fine test dust with a similar gravimetric loading, the filter blocked up in under half the time, as depicted by the green line. The brown and the yellow lines show the performance of another media with very similar efficiency. However this time when tested with ISO ultra-fine test dust, it achieved almost 30% more life than when it was tested with ISO medium test dust. Filtration efficiency and performance are functions of the type and size distribution of the dust the media is collecting.

A conclusion that may be drawn from this data is that the classification of dust through upstream bulk filtration may significantly affect the filtration required for on engine applications. If fuel is pre-cleaned in bulk storage to ISO 18/16/13, as recommended by the Worldwide Fuel Charter, then the downstream filtration on the engine may need to be more carefully matched to the incoming fuel to retain dirt and prevent wear.

CONCLUSION



32

CARE OF FUEL SYSTEM

The most important item in the handling of Diesel fuel is to keep it clean. Ninety per cent of Diesel troubles are due to dirt or water in the fuel. For successful operation it is necessary that these impurities be kept out of the fuel.

Keeping the fuel clean is the most important item to have in mind when provisions are made for storage of the fuel. If a pump is used to draw the fuel from the storage tank, the lower end of the suction pipe should be at least five inches[1] above the bottom of the tank. Taps on elevated tanks should be the same distance above the tank bottoms.

Whatever method of storage or filling is used, see that only clean fuel enters the tank. Be sure that the cans, funnels, hose or other equipment used for refueling are kept absolutely clean. If refueling is necessary when it is raining or dusty, protect the openings of storage containers, fuel tank and other equipment.

FUEL INJECTION

1—Main fuel tank. 2—Fuel suction manifold. 3—Fuel pump connections. 4—Fuel return line. 5—Main fuel line. 6—Fuel transfer pump. 7—Fuel filter. 8—Fuel injection pump.

Diesel Fuel System Care in 1931:

The first paragraph on system care from the 1931 operators manual states that 90% of diesel troubles are due to dirt or water in the fuel.

Figure 17. Caterpillar Diesel Fuel System Care 1931[7]

Ironically, the kind of systemic solution that is required to effectively address the issues outlined in this paper, seems to have been addressed in a 1931 excerpt titled "Diesel Fuel System Care:"[7]

> Ninety percent of diesel troubles are due to dirt or water in the fuel. For successful operation, it is necessary that these impurities be kept out of the fuel.

By 2010, it is widely predicted that diesel fuel injection systems will require much higher efficiency filtration below 5µm. Fuel will need to be in the order of 1,000 times cleaner than it is sometimes delivered today. ***The question is, how best can we achieve this?***

- Providing clean fuel throughout the distribution channel will become a prerequisite for diesel engine applications. Clear and bright standards will most likely have to make way for more precise measurable standards.
- The filtration industry will have to develop new technologies to measure fine particulate contaminants and design new filtration models to simulate and measure filtration performance.
- All stakeholders will need to actively participate in the development and maintenance of new standards for fuels and their filtration.
- Fuel companies, fuel distributors, fuel additive suppliers, engine manufacturers, fuel injection pump manufacturers and filter companies will have to work closely together throughout the supply chain, not just on the vehicle in order to deliver customer satisfaction.
- Filtration solutions will need to become system designs, not individual, application driven solutions.

ACKNOWLEDGEMENTS

The author would like to recognize the contributions of Derek Jones and Larry Moore of Donaldson Corporate Technology.

REFERENCES

1. Verdegan, B., True-Dahl, A., Haberkamp, W., Blizard, N., Genter, D, & Quillen, E., *Filtration Solutions for High Pressure Common Rail Fuel Systems*, AFS Conference, May 2008.
2. LaVallee,G. & Johnson, P., "How Flow and Vibration Affect Filter Performance Inside and Outside the Laboratory," *Machinery Lubrication Magazine*, May 2003.
3. *World Wide Fuel Charter*, Fourth Edition, September 2006.

4. Projahn, I. U., *Requirements for Diesel Fuel Injection Equipment and Fuel Quality Under Consideration of Global Market Aspects*, Fifth International Filtration Conference, October 2002. (with permission of SwRI)

5. Bessee, G., *Filter Wear Index—Pressure—Side Applications*, Fifth International Filtration Conference, October 2002. (with permission of SwRI)

6. Sayles, R. S. & Macpherson, P. B., *Influences of Wear Debris on Rolling Contact Fatigue*, ASTM 1982.

7. Douglas, R., *Improving Fuel System Durability*, Fifth International Filtration Conference, October 2002. (with permission of SwRI)