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A Method for Meaningfully Evaluating the Performance of a By-Pass Centrifugal Oil Cleaner

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ABSTRACT

By-pass filtration of engine lubricating oils is now a widely used technique for controlling the cleanliness of the oil during a vehicles service interval. The two common by-pass filtration techniques used by the automotive industry being barrier media filtration and self-driven centrifugal oil cleaners. In general it can be said that the fundamental operating principles of a centrifugal oil cleaner are poorly understood by others. The aim of this paper is to raise the general level of understanding of centrifugal oil cleaners and to aid lubrication system designers in the comparison of these devices with other filtration techniques.

This paper initially discusses the reasoning behind by-pass oil filtration and then goes on to assess some of the fundamental operating parameters which need to be addressed when fitting a self-driven by-pass centrifugal oil cleaner. Methods for determining the cleaning performance of traditional barrier media filters are adequately covered in the SAE standards J1858, HS-806, J1985 and ISO standard 4572. A standard method for evaluating the performance of a centrifugal cleaner is not well defined however. This paper sets out simple procedures and analysis techniques for the representative comparison of by-pass barrier media filters with centrifugal oil cleaners, thus enabling meaningful and repeatable testing to be performed.

INTRODUCTION

Most lubrication system designers are now well aware of the roll that by-pass lube oil cleaning plays in maintaining lube oil performance through the many papers that have been presented on the subject over recent years [1][2][3][4]. By-pass filtration of engine lubricating oils, particularly diesel engine lubricating oils, is now a widely accepted technique for controlling the cleanliness of the lube oil during a vehicles service interval. Industry currently uses two common by-pass filtration techniques, barrier filtration employing high performance low pore size filter media which needs a large surface area in order to sustain service life, and self-driven centrifugal oil cleaners which use the centrifugal sedimentation principle of separation to clean the lubricating oil.

In general barrier media filtration is reasonably well understood by designers since this type of filter media has been used for many years in full-flow oil filters. There are a number of standard test procedures for evaluating the cleaning performance and contaminant holding capacity of barrier media filters. Unfortunately, the fundamental operating principles of a self-driven centrifugal oil cleaner are less well understood by many in the lubrication industry, and there are no specific and applicable standard test procedures.

The best method of testing any filter is in the actual environment in which it is designed to operate. For engine lube oil filters this means running expensive and time consuming engine and vehicle tests. Standard tests and procedures such as SAE J1858, HS-806, J1985 and ISO 4572 [5][6][7][8] have been developed to allow engineers to evaluate the performance characteristics of traditional barrier media filters without resorting to engine tests. There is as yet no standard for evaluating the performance of a centrifugal oil cleaner and unfortunately in recent years several poorly planned and badly thought-out tests have been performed resulting in inaccurate and misleading information circulating within the industry. Techniques for establishing representative comparisons of by-pass barrier media filters with centrifugal oil cleaners have also not been standardised and similar problems exist.

We have found that the understanding of centrifugal sedimentation theory within the filtration industry is limited. Several papers have been presented on the subject of centrifugal separation in the past, however these mainly cover motor driven centrifuges which are subtly different in both design and operation [9].

This paper attempts to address these issues by aiding the lubrication system designer in his/her understanding of the fundamental principles which lie behind the operation of self-driven by-pass centrifugal oil cleaners. This is achieved in two ways, firstly by discussing the basic operating principles and installation factors which need to be considered when designing any by-pass filtration system onto an engine, in particular a self-driven centrifugal oil cleaner.

Secondly, procedures are proposed in which the cleaning performance of a traditional barrier media filter can be realistically compared with centrifugal oil cleaners.

In the absence of any comprehensive standard for the testing and comparison of centrifugal oil cleaners, we have developed our own testing procedures and analysis techniques for this purpose. These procedures are dependent upon the contaminant the filter is likely to be subjected to in service and represent closely the actual service conditions of the unit. For transmissions, hydraulics and industrial fluid applications ISO 12103-1 Filter Test Dust (Medium) [10] (also known as Standard Arizona Test Dust, SAE 5 - 80μm) is used as the test contaminant. For engine lube oil applications (particularly for diesel engines) SoftC-2A [11] is used. Analysis techniques are presented to enable comparisons between the cleaning performance of self-driven by-pass centrifugal oil cleaners and by-pass barrier media filters. Also contained within this paper is a resume of several of the issues relating to the successful installation and operation of a self-driven by-pass oil cleaning centrifuge within an engine oil lubrication system.

It is intended that this paper should become a source of reference for lubrication system designers, assisting them in the selection and implementation of appropriate centrifuge technology.

LUBE OIL FILTRATION SYSTEMS

A modern engine lubricating system as illustrated in figure 1 normally contains a mechanically driven oil pump, an oil pressure relief valve, an oil cooler and a combination of oil filters. Today nearly all force flow engine lubrication systems contain a full-flow filter downstream of lube oil pump which is used to stop any contaminant particles greater than the pore size of the filter getting to the bearings and other lubricated parts. By-pass filters, which filter a small proportion of the full flow and return it to the sump, are also used extensively especially in diesel engine lube systems.

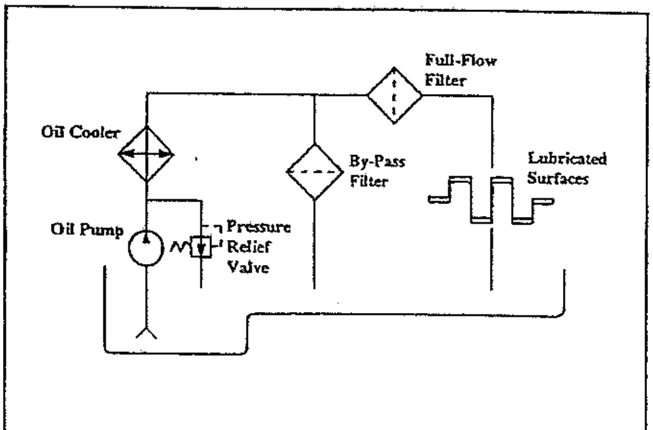


Figure 1 - A Typical Modern Engine Lubrication System

Full-flow filters are typically of the barrier media type as shown in figure 2. The pore size ratings of typical full-flow filters for engine applications are normally quoted at between 15 - 50μm (differences often stem from confusion over the use of absolute vs. nominal filter ratings). Recent work has shown that primary soot particles (the main particulate contaminant in a modern diesel lube oil) have sizes in the range 20 - 30nm and these primary soot particles fuse together to form larger particles in the range of 0.2 - 0.3μm [12][13][14][15]. Through our literature survey of the behaviour of soot in lube oil, the consensus of opinions is that these larger agglomerations of soot form the pro-wear particles in the lube oil whereas the smaller primary soot particles cause oil thickening which in turn reduces the lubricating properties of the oil and increases engine power consumption.

It is clear that the level of fine contaminant particles needs to be controlled however conventional full-flow barrier media filters are at best an order of magnitude larger in pore size than the majority of particles circulating in the lube oil. Full-flow filters therefore are only capable of removing the large particles which would cause catastrophic engine failure and are not capable of controlling combustion debris. Ever increasing amounts of combustion debris are being generated by modern engines and with tighter exhaust gas emissions regulations a large amount of contaminant is finding its way into the lube oil [16]. To combat the increased contaminant loading being placed on modern lube oils, lubrication system designers have in addition to full-flow filters, turned their attentions to by-pass filtration techniques as a means of controlling contaminant build-up in the lube oil.

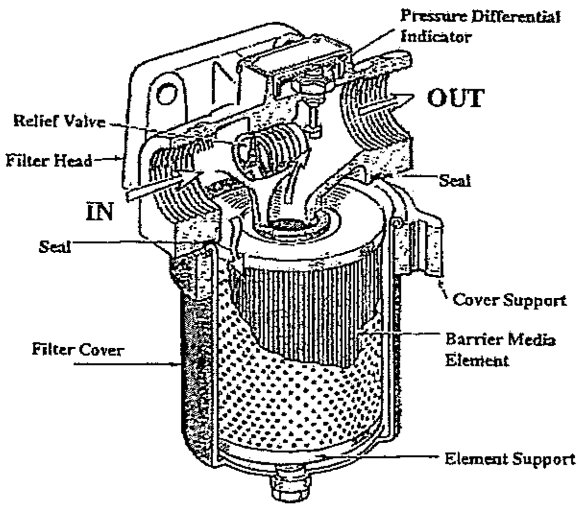


Figure 2 - Construction of a Typical Barrier Media Filter

By-pass filtration, as its name suggests filters or "cleans" the lube oil to a high level of cleanliness in a by-pass loop. The principle of by-pass filtration is to remove some of the oil from the lubricating system, pass it through a filter where a significant proportion of the contaminant is removed. This cleaner oil then either return to the sump (figure 1) or entrained back into the full-flow by use of a venturi [17].

This is a continuous process whenever the engine is operating and the cleanliness level that can be achieved will be dependent upon by-pass filter flow [illegible], sump size, ingression rate, by-pass filter instantaneous efficiency and capacity. Typically <10% of the oil supplied by the oil pump is used for by-pass filtration.

BY-PASS OIL FILTRATION - By-pass lube oil filtration is becoming increasingly popular with the worlds diesel engine manufacturers as a way of controlling the level of contaminant in the lube oil by removing and storing it. In Japan diesel engine manufacturers have been using increasingly complex combination barrier media full-flow and by-pass filters for many years. In Europe Scania, Renault and DAF are using self-driven by-pass centrifugal oil cleaners as are Mack in the US and a raft of other engine manufacturers around the world.

The benefits of using continuous by-pass filtration in conjunction with a traditional full-flow filter are two-fold. Firstly, cleaning the oil through a by-pass filtration process removes many of the very small contaminant particles that would go straight through a full-flow filter as well as removing some of the relatively large particles that would have normally been stopped by the full-flow filter. Hence, the use of by-pass filtration can extend the life of the full-flow filter. This gives the lubrication system designer the opportunity to either use a physically smaller full-flow filter or possibly to extend the oil drain period [18][19][20]. Secondly, an appropriately sized by-pass filter can remove the small pro-wear contaminant particles thus extending engine component life [3][4][21].

By-pass barrier filtration - From the information presented above and in the referenced papers it could be concluded that to effectively clean engine lube oil a very fine (<1μm) full-flow filter is needed. Such a filter would remove many of the pro-wear particles and as it became occluded would remove also some of the primary soot particles. Unfortunately a full-flow barrier media filter of such a fine rating would need to be extremely large to sustain an acceptable pressure drop and flow rate. In by-pass filtration only a small proportion of the full-flow (≈10%) is passed through the low pore size by-pass filter before either being returned to the sump or being entrained with the full-flow. Therefore, a filter that needs to pass a flow of ≈10% of its full-flow counterpart and which can tolerate a total pressure drop (total pressure drop = supply pressure - 0) across it gives a more practical solution.

Unfortunately, barrier media by-pass filtration of the type described here has several drawbacks in use. Firstly as the filter collects contaminant the flow rate through the filter drops, quickly approaching zero. It is our experience that some by-pass filter media's rupture or "channel" as the flow rate drops allowing some of the collected contaminant back into the system. Decreasing flow with increasing time means that the amount of contaminant being removed from the oil reduces over time, therefore assuming a constant ingression rate, the level of contaminant in the oil increases more rapidly with time. This is acceptable (but not desirable) in a by-pass barrier media filter as long as the by-pass filter continues to operate effectively for a period of time equally as long as the full-flow filter operates effectively (i.e. full-flow filter by-pass valve remains closed). However, in many full-flow and by-pass systems this is not the case.

Barrier media filter ratings are normally quoted as either the Filtration Ratio β, or Filtering Efficiency η. The β ratio is evaluated by dividing the particle count greater than a given size (normally stated in microns, μm) entering the filter C_{Up} by the particle count greater than the same size leaving the filter C_{Down}.

$$\beta = \frac{C_{Up}}{C_{Down}} \qquad (1)$$

The particle count size being normally expressed as a subscript e.g. a filter with a rating of "β_3=200" would for every 200 particles greater than 3μm entering the filter upstream allow only 1 to pass through it. The Instantaneous Filter Efficiency η (sometimes referred to simply as the Filter Efficiency) is also normally quoted for particles greater that a given size in microns, μm. It is defined as the Upstream - Downstream Particle Counts of a given size divided by the Upstream particle count. This can be expressed in terms of the β ratio as

$$\eta_x = \left(1 - \frac{1}{\beta_x}\right) \times 100. \qquad (2)$$

Multi-pass filter test standards such as J1858 and ISO 4572 evaluate these filter efficiencies over a finite time period as the filter blocks. Hence, the differential pressure drop measured across the filter increases during this time. In J1858 the time taken for a filters initial pressure drop to increase by 80% and 100% is recorded and particle counts upstream and downstream are taken simultaneously every 10 minutes. Whereas in ISO 4572 the time taken for a filters initial pressure drop to increase by 5%, 10%, 20%, 40%, 80%, and 100% is recorded. J1858 specifies an oil conforming to SAE J1260 [22] and the contaminant is specified as SAE 5 - 80μm (ISO 12103-1). In ISO 4572 the oil type is specified within the standard and the contaminant to be used is specified as Air Cleaner Fine Test Dust or any other ISO-approved equivalent.

By-pass centrifugal oil cleaners - An alternative form of by-pass filtration device is the centrifugal oil cleaner. These fall into two broad categories of powered and self-powered. The powered type are generally large and expensive units however these have found extensive applications in process industries and on very large marine diesel engines for the cleaning of both the fuel and lubricating oils. Self-powered centrifugal oil cleaners are generally much smaller than their powered counterparts and have found applications in many fluid cleaning processes such as industrial quench oil and hydraulic oil cleaning.

The main area of application however remains medium and high speed diesel engine lubrication systems.

A self-powered centrifugal oil cleaner uses the oil supplied to it to be cleaned, which is supplied under pressure, to drive the cleaning rotor, hence the term self-powered. Once cleaned the oil returns to the sump. A centrifugal oil cleaner uses the principle of centrifugal sedimentation to separate particles of different densities. The majority of contaminant particles found in the lubricating oil of a diesel engine, such as wear metals and soot, have higher densities than the lubricating oil, therefore subjecting the oil to a high centrifugal force causes separation of the contaminants from the oil. In a self-driven by-pass centrifugal oil cleaner these contaminants collect as a hard cake on the inside of the rotor (figure 3) which can then either be cleaned out or disposed of as a unit and replaced with a new unit at the oil drain service interval.

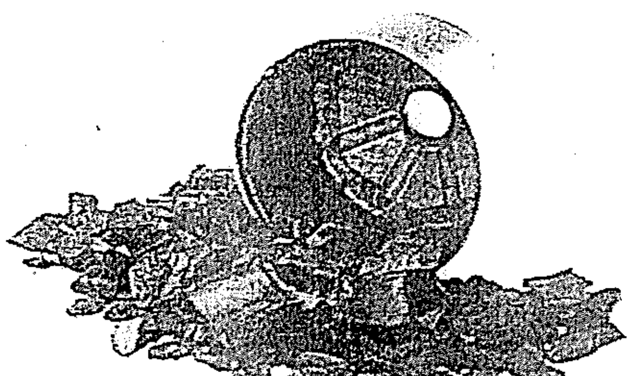


Figure 3 - An Open Centrifuge Rotor From The Lubricating System Of A Diesel Engine Reveals A Typical Deposit Of Removed Contaminant

A centrifugal oil cleaner has two major advantages over a barrier media filter. Firstly the cleaning efficiency of a centrifuge remains constant throughout the service interval (providing the centrifuge has been correctly selected to match the ingression rate of contaminant and sump size). Secondly, the lower limit to particle size which can be removed by a centrifugal oil cleaner is the point where the viscous drag forces between the fluid and the particle equal the centrifugal force to which the particle is subjected. In practice this lower limit is well below 1μm in a typical installation. Therefore, an efficient centrifuge can remove the pro-wear contaminants and the primary soot particles that cause oil thickening throughout the service interval [23].

Retro-fitting of self-powered centrifugal oil cleaners to vehicles in the field has resulted in better control of oil contaminant particles and viscosity during the vehicle's service interval. In many such cases it has been possible to extend the oil drain period by the addition of a self-powered by-pass centrifugal oil cleaner to the lube oil system [2].

The impact of self-powered centrifugal oil cleaners on the environment is considerably more positive than that of barrier media filters. Centrifugal oil cleaners are designed either to be cleanable or disposable depending on their application and retain considerably less oil when drained than its barrier media equivalent.

By combining a cleanable centrifugal oil cleaner with a cleanable full flow barrier filter, such as a metal screen, a completely cleanable lube oil filtration system becomes possible. This system is becoming more common on trucks in the US. The use of a cleanable centrifugal oil cleaner and cleanable full-flow screen is seen as a major contribution toward reducing the amount of hazardous waste produced by IC engines and toward more efficient use of the earth's natural resources.

OPERATING PRINCIPLES AND THEORY OF SELF-POWERED OIL CLEANING CENTRIFUGES

The operating principles of centrifugal oil cleaners are simple but poorly understood. With reference to figure 4, a small proportion of the total system oil flow (≈10%) enters the vertical hollow spindle on which the rotor is supported. Oil exits the spindle via a cross drilling into a transfer chamber in the rotor. Oil in the transfer chamber is in direct contact with the bearings at either end of the rotor, thus providing them with pressurised lubrication. Oil exits the transfer chamber via two slots and enters the cleaning chamber of the rotor. The contaminated oil then circulates around the cleaning chamber, being accelerated up to the same rotational speed as the rotor. Contaminants which are more dense than the fluid are deposited on the inner surface of the rotor wall via centrifugal sedimentation.

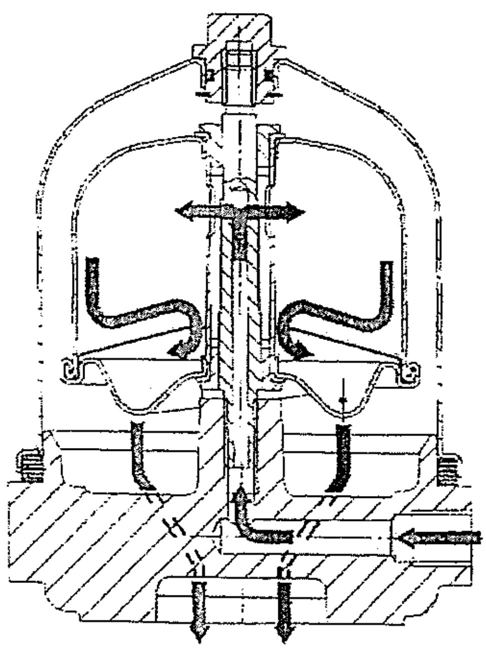


Figure 4 - Centrifugal Oil Cleaner Principles of Operation

The cleaned oil flows from the cleaning chamber of the rotor into the lower drive chamber via an annular opening in the shallow cone which separates the two chambers. Once in the drive chamber the oil exits via a [illegible] of tangentially opposed nozzles in the base.

The oil leaving the rotor creates a reaction force at the nozzles causing the rotor to spin. The drive chamber of a centrifugal rotor being normally smoothly contoured to reduce fluid losses as the oil is transferred to the nozzles.

CENTRIFUGAL SEDIMENTATION - Centrifugal sedimentation is the key to how and why a centrifugal oil cleaner works. The basic principle can be explained thus: Consider a spherical contaminant particle of diameter d_p and density ρ_p suspended at radius r in a fluid with density ρ_o and dynamic viscosity μ_o. Consider further that the particle and fluid system is rotating at a constant angular velocity ω about a vertical axis, as shown in figure 5. Assuming the fluid and the contaminant particle to be both rotating about the vertical axis at the same angular velocity ω, then the centrifugal force f_c acting on the particle is given by

$$f_c = m_p r \omega^2 \qquad (3)$$

where m_p is the mass of the particle. Opposing this force there is a drag force f_d which will be a function of the Reynolds number and particle drag coefficient. Assuming also that the Reynolds number for any flow over the spherical contaminant particle is small enough for Stokes' Law to be valid then it can be shown that the time τ needed for a particle to travel a distance Δr from a start point at r to the rotor wall is given by

$$\tau = \frac{18\mu_o \ln((r + \Delta r)/r)}{d_p^2 \Delta\rho \omega^2} \qquad (4)$$

where $\Delta\rho$ is the difference in density between the contaminant particle and the oil ($\rho_p - \rho_o$).

From equation (4) it can be seen that the lower the viscosity the easier it is for a particle to travel through the oil and hence be removed from it. Secondly, for a given set of conditions, the shorter the distance Δr a particle has to travel to come into contact with a wall, the smaller the size of particles that can be removed. It should also be noted that the dominant terms in equation (4) are the two squared terms d_p and ω. Particle diameter (d_p) is a function of the contaminant however rotational speed (ω) can be influenced by the designer. The importance of maximising ω is clear.

It can be seen that increasing the speed of rotation decreases the time taken τ for the particle to travel the distance Δr to become trapped on the rotor wall. Simplifying the relationship, the faster the centrifugal oil cleaning rotor spins, the greater its cleaning efficiency (assuming the same centrifuge geometry). Conversely for a given time τ, increasing the speed of the centrifuge rotor will result in the a reduction of the minimum particle size (for a given density) that can travel the distance Δr in that given time.

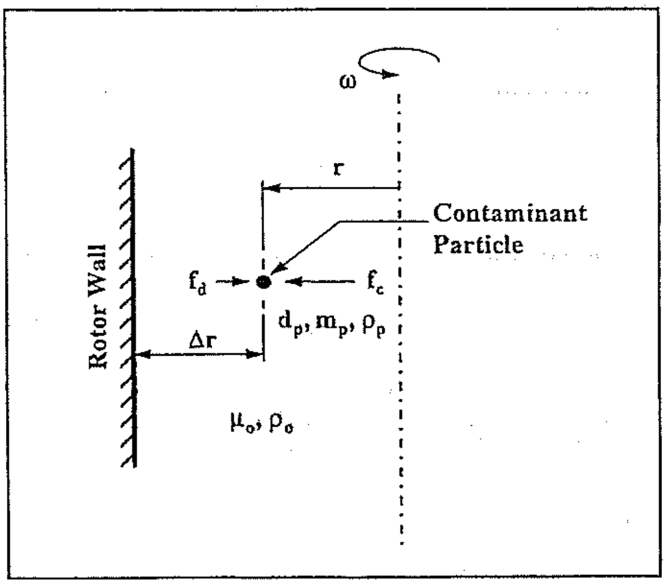


Figure 5 - Centrifugal Sedimentation

From the centrifugal sedimentation analysis above it is possible to plot the single pass filtering efficiency η of a centrifugal oil cleaner for a particle/fluid system with a given density difference, $\Delta\rho$ on the vertical axis against particle size on the horizontal. η is defined as upstream - downstream particle counts greater than a given size divided by the upstream particle count. This results in a curve of the form given in figure 6. The horizontal position of this curve being a function of the terms in equation (4). Increasing the residence time τ, the radius of rotation r and the speed of rotation ω moves the curve to the left and hence smaller particles are removed. Similarly decreasing the distance a contaminant particle needs to travel Δr and the viscosity of the oil μ_o also moves the curve toward the Y - axis.

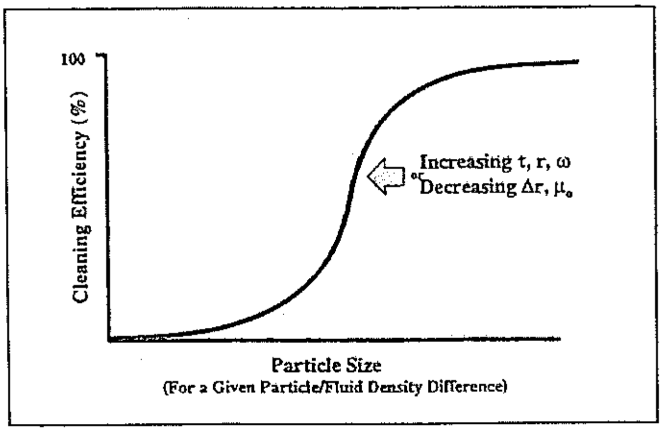
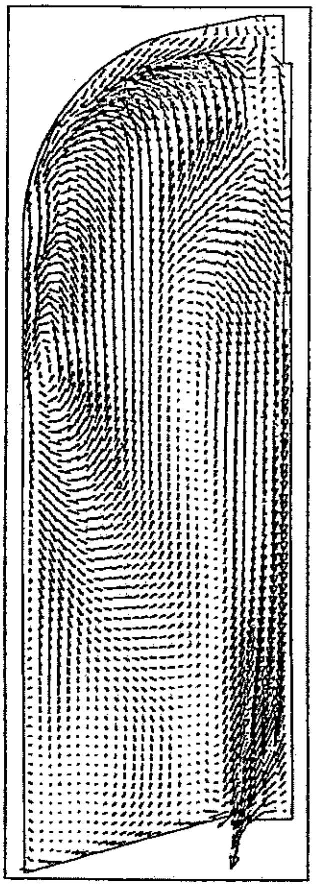


Figure 6 - Oil Conditioning Considerations that Effect Centrifuge Cleaning Efficiency

ROTOR DESIGN - Computational Fluid Dynamic (CFD) analysis of a disposable centrifuge rotor (figure 7) shows velocity vectors and hence flow paths of the oil through the cleaning chamber of the rotor.

It can be seen that the oil flow is divided with a substantial proportion of the fluid passing up under the rotor cover and flowing down the rotor wall. Oil is then recirculated back up towards the inlet port, eventually exiting the chamber by flowing down the outside of the centre bearing tube.



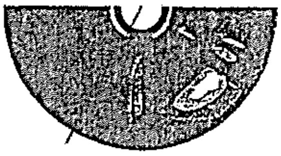


Figure 7 - CFD Analysis of Oil Flow Inside The Rotor Cleaning Chamber

It should be noted that within the rotor there will exist a pressure gradient which is increasing towards the wall of the rotor as shown in figure 8. This phenomena is caused by the increase in centrifugal force as a function of the radius r. A proportion of the energy supplied to the rotor is thus used in forcing the fluid entering the rotor towards the outer wall against the increasing pressure gradient. Another important factor to be considered as a consequence of the pressure gradient caused by rotation is the structural integrity of the rotor.

The centrifugal oil cleaning rotor has been designed to maximise particle residence time τ whilst maintaining an almost unrestricted flow of oil around the centrifuge cleaning chamber resulting in very little pressure energy losses. This then maximises the available energy at the tangentially opposed drive nozzles. Momentum transfer from the fluid exiting these nozzles is therefore maximised enabling high rotor speeds to be achieved.

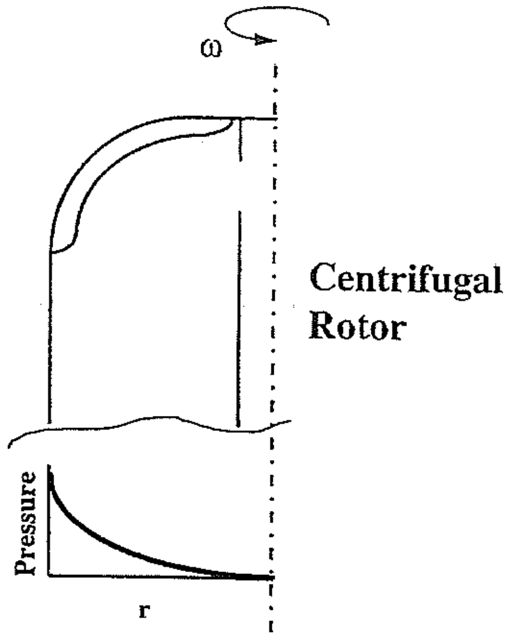


Figure 8 - Pressure Gradient in a Spinning Centrifuge Rotor

INSTALLATION CONSIDERATIONS - There are two main installation consideration to be observed when designing a self-powered by-pass oil cleaning centrifuge onto an engine's lube oil system. These relate to the condition of the oil supplied to the centrifuge and draining of the cleaned oil away from the centrifuge.

Oil supply - For the most efficient operation of a centrifugal oil cleaner it is important, for the reasons discussed earlier, that oil reaches the centrifuge in the optimum condition. This effectively means that the oil should be hot, so that the viscosity is at its lowest, and supplied at high pressure so that the centrifuge rotor spins at its fastest. Therefore, on an engine application, the ideal oil supply tapping point for a by-pass centrifugal oil cleaner is immediately downstream of the oil pump as shown in figure 9. The next best position being downstream of the oil cooler and upstream of the full-flow filter, with the least preferred position being downstream of the full-flow filter.

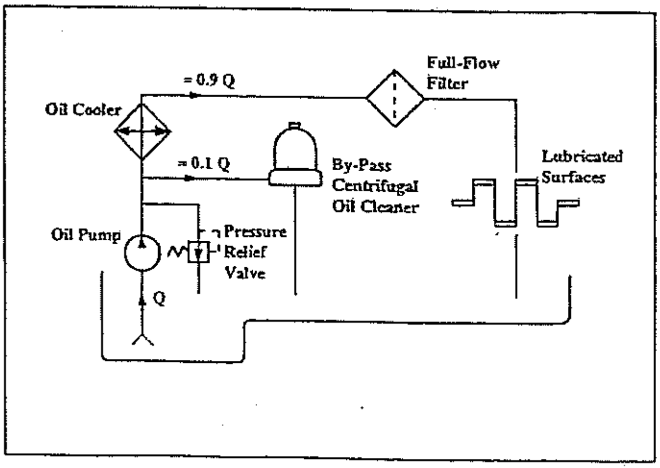


Figure 9 - Preferred Centrifuge By-pass Oil Supply Tapping

In addition to tapping position, consideration should be given to ensuring that the oil supply galleries to the centrifuge are as short as possible and of adequate size to minimise pressure energy losses.

drainage - Oil drainage is vital to the efficient operation of a centrifugal oil cleaner. Oil exiting from the rotor nozzles must be able to escape freely and allowed to return to the sump. Flooding of the rotor occurs when the drain passage is insufficient to allow natural atmospheric drainage of the centrifuge rotor housing. This causes the oil level to rise impinging on the rotor thus reducing its speed.

Problems associated with drainage can easily be avoided by ensuring a sufficient size of drain and endeavouring to return the oil to the sump above the normal oil level, thus allowing air to travel up the drain pipe and maintain a free airspace around the rotor.

LABORATORY TESTING BY-PASS CENTRIFUGAL OIL CLEANERS WITH ARTIFICIAL CONTAMINANT

aim of laboratory filtration testing is to evaluate the cleaning and structural performance characteristics of a filter in a controlled environment. It is often desirable that the conditions under which the performance characteristics are evaluated during the test mimic those observed in service. Centrifugal sedimentation relies on differences in the contaminant and oil density to remove particles, whereas barrier media filters remove contaminant particles based on particle size. To make a meaningful comparison between a traditional barrier media filter and a centrifugal oil cleaner one must ensure that the same test conditions and contaminant are applied to both filters. To meet these testing requirements it is very important (particularly for centrifugal sedimentation devices) to select an artificial contaminant that is representative of the actual contaminant to which the filter is likely to be subjected in service. For these reasons we have developed centrifuge testing specifications centred ınd two basic test contaminants.

If the filter is to be used in a transmission/hydraulic fluid power circuit where the contaminant ingress consists mainly of hard particles such as metallic debris and silica, then the appropriate test contaminant would be ISO 12103-1 Medium Grade Test Dust as specified for the multi-pass filter test J1858. Depending on the application this may be cut with Iron (Fe) particles to represent metallic wear materials. Alternatively, for application to internal combustion engine lube systems (particularly for diesel engines) the most suitable standard test contaminant has been found to be SoftC-2A.

ISO 12103-1 Medium Grade Test Dust consists mainly of SiO_2 (68 - 76% by weight) and Al_2O_3 (10 - 15% by weight), the remainder comprising small amounts of Fe_2O_3, Na_2O, CaO, K_2O, MgO, and TiO_2. This test dust , a particle size range <80µm with 15 - 19% being smaller than 5µm. For tests with added Iron it has been found suitable to use Electrolytic Reduced Iron powder cut between 0 - 45µm, mixed in the ratio 40% Fe to 60% ISO 12103-1 Medium Grade Test Dust by weight.

SoftC-2A, is a mixture of contaminants and mineral oil (22% and 78% by weight respectively). The contaminant being made up of 73% by weight carbon black powder with an average particle size of 0.7µm, 9% by weight ferric oxide of which 95% by volume is between 0 - 5µm, with the remaining 18% consisting of PV resin particles with a size range < 30 mesh (approximately 800µm).

In house analysis of SoftC-2A and a typical contaminated diesel lubricating oil using a Horiba LA-910 Laser Diffraction Particle Size Analyser revealed the particle size distribution for contaminated lube oil to be in the range 90nm - 1.5µm with a median of 0.28µm. Similar results for SoftC-2A indicate a size distribution range of 150nm - 1.9µm with a median of 0.59µm. This indicates that SoftC-2A particles are on average slightly larger in size than real diesel contaminant, however, since real diesel lube oil contamination consists mainly of soot, and SoftC-2A contaminant consist mainly of carbon black, the effective densities are very similar.

CONTAMINANT TEST PROCEDURE AND ANALYSIS FOR TRANSMISSION/HYDRAULIC APPLICATIONS USING ISO 12103-1 MEDIUM GRADE TEST DUST

Our procedure for the testing of by-pass filtration devices for use in transmission/hydraulic fluid applications is based loosely on the SAE multi-pass filter tests J1858 and HS-806 and ISO 4572. However, since a centrifugal oil cleaner exhibits **no** change in flow rate or pressure drop across the device during its service life (unlike a barrier media filter) the instantaneous filter efficiency η cannot be evaluated as a function of pressure drop as specified by barrier media multi-pass filter tests. Therefore, it is necessary to take a different approach when comparing a barrier media filtration device with a centrifugal oil cleaner. The technique used still evaluates the instantaneous efficiencies η of both devices, however, to evaluate the performance of the filtration device over time the cumulative efficiencies ε are calculated and compared.

EVALUATING THE INSTANTANEOUS FILTER EFFICIENCY η - The instantaneous filter efficiency η for contaminant particles greater than a given size n of a barrier media filter can be evaluate as a function of the filter's pressure drop through the multi-pass filter test (ISO 4572 or SAE J1858). The instantaneous filter efficiency η for contaminant particles greater than a given size n of a centrifugal oil cleaner can be evaluated either from a continuous addition test or a clean-down test as described below.

Evaluating η for a centrifugal oil cleaner from a continuous addition test - Consider a sump of volume V contaminated with C particles >n µm which pass through a centrifugal oil cleaner having and instantaneous filter efficiency η_n with a flow rate Q.

The rate of removal of particles R from the sump is given by

$$R = -\eta_n \frac{Q}{V} C_n . \quad (5)$$

If particles are added to the sump at a rate of $\delta c_n/\delta t$ which is independent of C_n then the rate of change of particles in the sump is given by

$$\frac{dC_n}{dt} = \frac{\delta c_n}{\delta t} + R , \quad (6)$$

substituting equation 5 and rearranging gives

$$\frac{dC_n}{dt} + \eta_n \frac{Q}{V} C_n = \frac{\delta c_n}{\delta t} . \quad (7)$$

Multiplying through by $e^{\eta_n \frac{Q}{V} t}$ and integrating gives

$$C_n = \left[\frac{\delta c_n}{\delta t} \frac{V}{\eta_n Q} - \frac{K}{e^{\eta_n \frac{Q}{V} t}} \right]_0^{\to\infty} \quad (8)$$

where K is a constant of integration.

Assuming the contaminant level to be zero at time t=0, then the total contaminant in the sump at any time t is given by

$$C_n = \frac{\delta c_n}{\delta t} \frac{V}{\eta_n Q} \left(1 - e^{-\eta_n \frac{Q}{V} t} \right) . \quad (9)$$

As t tends to infinity and assuming no change in η_n, $\delta c_n/\delta t$, Q, and V, then C_n becomes stable i.e. the amount of contaminant removed per unit of time equals the amount of contaminant added during the same period of time,

$$\therefore \; C_n = \frac{\delta c_n}{\delta t} \frac{V}{\eta_n Q} \quad \text{as } t \to \infty . \quad (10)$$

The instantaneous filter efficiency η_n can therefore be evaluated from

$$\eta_n = \frac{\delta c_n}{\delta t} \frac{V}{Q C_n} . \quad (11)$$

Due to the extended periods of time required to achieve reliable results by this method it is often more practical to perform a clean-down type test (sometimes known as a draw-down test).

<u>Evaluating η for a centrifugal oil cleaner from a clean-down test</u> - A somewhat easier way of determining the instantaneous filter efficiency η of a centrifugal oil cleaner is from a clean-down test. In the clean-down test the test oil is first cleaned to an appropriately low contamination level prior to testing. This oil is then circulated through the centrifuge to be tested at a supply pressure and temperature determined from its likely service conditions. A predetermined amount of contaminant is then added to the sump and particulate levels monitored at intervals over the next 2-3 hours as the oil is cleaned by the centrifuge. From the analysis of particulate levels as a function of time the instantaneous filter efficiency can be calculated. The method of calculation is given below.

Consider a sump of volume V contaminated with C particles >n µm which passes through a centrifugal oil cleaner with a flow rate Q. If we assume the oil and the contaminant to be homogeneously mixed and make the assumption that the instantaneous filter efficiency of the cleaner η is independent of the contaminant level, then the rate of change of contaminant in the sump can be expressed as

$$\frac{dC_t}{dt} = -R \quad (12)$$

where R is the contaminant removal rate and C_t the level of contaminant at any time t. The contaminant removal rate R can also be expressed as

$$R = \eta C_t \frac{Q}{V} \quad \text{at any time t} \quad (13)$$

where η is the instantaneous filter efficiency. Hence

$$\frac{dC_t}{dt} = -\eta C_t \frac{Q}{V}$$

$$-\frac{V}{\eta Q} \int_{C_0}^{C_t} \frac{1}{C_t} dC_t = \int_0^t dt \quad (14)$$

where C_0 is the level of contaminant at time t=0. Integrating gives

$$\frac{V}{\eta Q} \left(\ln C_0 - \ln C_t \right) = t . \quad (15)$$

Equation (15) can be rearranged in terms of the instantaneous filter efficiency η for particles >n µm, at any given time t thus,

$$\eta_n = \frac{V}{Qt} \left(\ln C_{n,0} - \ln C_{n,t} \right) . \quad (16)$$

Plotting the logarithm of the particle level C_n against time t produces a linear relationship, the gradient m of which gives

$$m = -\frac{V}{Q \eta_n} \quad (17)$$

EVALUATING THE CUMULATIVE EFFICIENCY ε - The cumulative efficiency ε of a by-pass filtration device is defined as the percentage by mass of total contamination entering the system which is removed by the filtration device as a function of time. The method suggested by both SAE J1858 and SAE HS-806 (chapter 2), and which can also be evaluated from the ISO 4572 multi-pass filter test, for evaluating the mass of contaminant removed by the filtration device is based on the subtraction of the mass of contaminant remaining at the end of the test from the mass of contaminant that has been added to the oil during the test. The suggested method for evaluating the mass of contaminant remaining in the oil is by Gravimetric analysis of a representative sample of test oil using a 0.8μm membrane filter.

Unfortunately, since these test specification are based on full-flow filter requirements, the results appear to show that the cumulative efficiency of a barrier media filter always increases with time. This is because the test is stopped when the initial filter element pressure drop has increased by a given amount (normally by 100% of its initial pressure drop). However, In real applications this is not a true representation. If the test was allowed to continue the instantaneous filter efficiency would continue to rise, tending toward 100%, but since the flow rate Q through the filter decreases with time (because the filter becomes occluded) the cumulative efficiency will fall off.

For any by-pass filtration device the point at which the cumulative efficiency peeks is effectively the end of the useful life of the filter. We can term this point the cumulative efficiency life τ_c of the filtration device. For a barrier media filter the cumulative efficiency life is a function of pore size, media type and surface area. Long cumulative efficiency life τ_c requires a filtration device with a large contaminant holding capacity. Unfortunately, space and weight considerations within the engine compartment will not always allow this and a compromise is drawn between pore size and filter size. The importance of this trade-off becomes clear when comparisons are made between different filter systems.

Comparing the cumulative efficiency of a barrier media by-pass filter of volume V with instantaneous efficiency η, with a centrifugal oil cleaner that has a similar volume V and instantaneous efficiency η, it can be shown that the centrifugal oil cleaner has a considerably longer cumulative efficiency life τ_c than an equivalent barrier media filter. A diagrammatic representation of this is shown in figure 10.

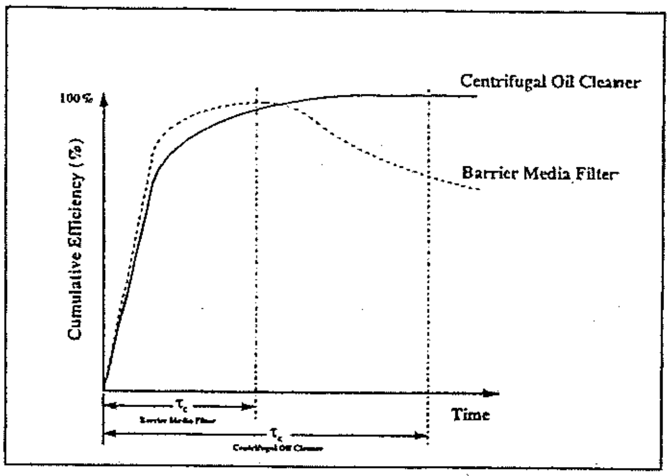


Figure 10 - Cumulative Efficiency Of Similarly Sized By-Pass Filtration Devices

For a centrifugal oil cleaner cumulative efficiency ε can also be written as

$$\varepsilon_n = \left[1 - \frac{1 - e^{-\eta_n \frac{Q}{V} t}}{\eta_n \frac{Q}{V} t}\right] \times 100 \qquad (18)$$

where η is the instantaneous filter efficiency, Q is the volume flow rate, V the sump volume, and the subscript n is the size of contaminant particles >n μm [1]. In equation (18) it is assumed that the volume flow rate Q and the instantaneous filter efficiency η do not vary during the life of the by-pass filter. For a centrifugal oil cleaner this assumption is valid, however, for a barrier media filter this is obviously not true.

CONTAMINANT TEST PROCEDURE AND ANALYSIS FOR I/C ENGINE LUBE APPLICATIONS USING SOFTC-2A

The method developed by us for comparative testing of by-pass filtration devices for use in engine (especially diesel engine) lube oils is based on a simulated engine lubrication system.

With reference to figure 11, oil is supplied by a circulating pump at elevated temperature and pressure to both a full-flow filter and a by-pass filtration device. The by-pass filtration device can either be a barrier media type or a centrifugal oil cleaner. The full-flow filter can be either a traditional media unit or a large pore size cleanable screen. Oil leaving both the full-flow and by-pass filters is returned to the sump. During the filter test SoftC-2A contaminant is added to the lube oil continuously at a fixed rate. The oil supply pressure, temperature and flow rate are monitored at 10 minute intervals throughout the test, as are the full-flow filter pressure drop and flow rate.

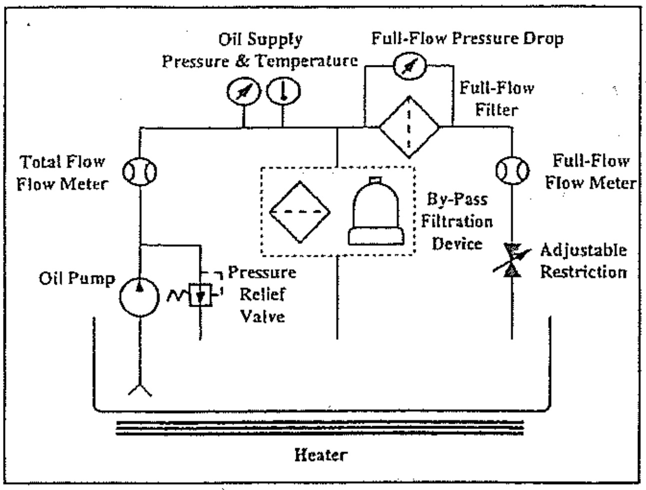


Figure 11 - Diesel Lubrication Oil Filter Test Circuit Using SoftC-2A

TEST-PROCEDURE - The full-flow and by-pass barrier media filters to be tested are set-up in the simulated engine lubrication system as described above. Clean test oil is circulated around the system to eliminate air from the filters. The filters are then removed from the test loop, topped-up with oil to the point of over flowing and weighed. The filters are replaced and the clean test oil is circulated at reduced pressure and flow rate while the oil and test components are brought up to temperature prior to starting the test. The duration of the test is dependent on ingression rate and size of test filters, however a typical test duration is between 48 - 60hrs. During the test, SoftC-2A is added at a fixed rate through continuous addition using a positive displacement pump, a typical continuous addition rate for a 15L sump would be approximately 20g/hr. The SoftC-2A reservoir is continuously agitated to ensure thorough mixing. Pressure and flow rate measurements are taken automatically initially at intervals of 10 minute until the point where the pressure drop across the full-flow filter is greater than 0.5Bar. At this point the sampling interval is decreased to 1 minute so that more data is gathered during the blocking period of the full-flow filter.

On completion of the test the filters are removed from the system, topped up with clean oil and weighed as before. Subtracting the start from the finish weights gives the change in mass Δm of each filter.

The system is then thoroughly flushed first with clean paraffin and then with low additive SAE10 lubricating oil prior to being re-filled with test oil and fitted with a new full-flow filter. The by-pass filter is replaced with a centrifugal oil cleaner and the test repeated. Note that the full-flow filter is weighed as before and the centrifuge rotor is weighed full of oil prior to and after testing.

The contaminant holding capacity of both barrier media filters and centrifugal oil cleaners can be determined from

$$m_c = \Delta m \frac{\rho_c}{\rho_c - \rho_o} \qquad (19)$$

where m_c is the mass of contaminant collected by the filter, Δm is the change in weight of the filter, and ρ_c and ρ_o are the densities of the contaminant and the test oil respectively. An estimate of the test terminal cumulative efficiency ε for the by-pass filter can be made from the contaminant holding capacity thus,

$$\varepsilon = \frac{m_{bp}}{m_{in}} \times 100 \qquad (20)$$

Where m_{in} is the mass of added contaminant (≈22% of the mass of SoftC-2A added) and m_{bp} is the mass of contaminant collected by the by-pass filtration device.

The aim of a by-pass filter is to keep the oil cleaner for a longer period of time. This generally results in an extension of full-flow filter life resulting from the reduced contaminant loading on it. By comparing the pressure and flow logs for each of the tested filtration combinations an estimate of full-flow filter life extension can also be made.

In the ideal full-flow and by-pass filtration system the pore size and contaminant holding capacity of the two filters should be matched to the lubrication system capacity, ingression rate and contaminant type. In this scenario both the full-flow filter and the by-pass filter would reach the end of their useful lives at the same point in time. That point should be slightly longer than the service interval. In reality it has been found that barrier media by-pass filters often have far shorter effective lives (cumulative efficiency lives τ_c) than the full-flow filters they are paired with.

SUMMARY

Lubricating oil is a vital component of all internal combustion engines and hydraulic systems and the condition of the oil is of paramount importance to the condition of the engine or hydraulic system. With OEM's now striving to produce cleaner engines with higher fuel efficiencies and longer service intervals, higher contaminant loadings are being placed on the lube oil. A similar situation exists within the fluid power sector where smaller valve clearances are being used to obtain greater control. Advances in oil technology combined with full-flow barrier filters alone can no longer handle the increasing contaminant loadings and ever extending service intervals. To control contaminant build-up in lube oil systems lubrication designers have turned their attention to by-pass filtration.

With the surge in interest in by-pass filtration techniques and particularly in centrifugal oil cleaners has come the realisation that many lubrication system designers have a poor understanding of the operating principles of centrifugal oil cleaners. Currently no standard tests are available which can meaningfully be

used to assess the performance of centrifugal oil cleaners. In addition to setting out the basic principles of centrifugal sedimentation this paper introduces two test procedures which use realistic contaminant and simulated service conditions to evaluate filter performance for both barrier media filters and centrifugal oil cleaning systems.

The definitive method of testing the performance of a filter system remains an engine or in service test in real conditions however good results can be obtained by following the methods set out in this paper. Filter systems that are to be used in hydraulic/transmission applications are tested using ISO 12103-1, A3 Medium Test Dust, and filters that are to used in engine lubricating systems are tested using SoftC-2A.

The two novel test techniques proposed in this paper are based around standard filter test methods such as SAE J1858 and good laboratory practice. It is believed that increasing use of these techniques will enable lubrication system designers around the World to form a clearer picture of the considerable capabilities of the oil cleaning centrifuge.

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