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# The Development of Lubricating Oils for Rotary Racing Engines

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## ABSTRACT

In order to achieve the highest power output and lowest fuel consumption for the rotary engine in endurance race such as Le Mans, two types of lubricating oils were developed by conducting a single rotor engine test at the rotational speed of 7500 rpm under full load. One was the engine oil for the lubrication of the combustion chamber. The other was a so called system oil for lubrication of the engine system outside the combustion chamber.

The conclusions obtained from the development are as follows :

**1 ) Engine oil for the combustion chamber**

The engine oil greatly influences spitback phenomenon which can cause rotary engine trouble in an endurance race. The spitback phenomenon is decreased by the decrease of carbonaceous deposit and ash in the apex seal grooves. The newly developed oil to improve this phenomenon consists of conventional ashless dispersant and synthetic base stock, which easily burns without forming a deposit.

**2 ) System oil**

The system oil significantly influences the fuel consumption of rotary engines. A thermally stable, high VI synthetic base stock was used as the base oil for the system oil in order to ensure engine reliability. Fuel saving was successfully achieved by the addition of an organic molybdenum compound as a friction modifier (FM) and lowering base oil viscosity without interfering with the protection from bearing surface failure. The addition of FM is expected to improve fuel consumption by 1 to 1.5% as well as lowering the surface temperature of the bearing metal to a significant extent. These two oils have been used for racing cars fitted with rotary engines since the 1989 Le Mans Race.

## INTRODUCTION

The rotary engine was developed by fundamental joint work of Doctor Felix Wankel and NSU Motorenwerke AG. The rotary engine has an ideal engine design because the rotational motion of the rotor is directly converted to engine power output by use of an eccentric shaft. However, there were many difficulties to be solved before it could be applied for practical use.

It had been about twenty five years since Mazda commercially manufactured a rotary engine in 1967. Passenger cars with rotary engines have been in steady use in worldwide markets since then. However, there are few published technical reports regarding the lubricating oil for the rotary engine.

This report intends to clarify the influence of the lubricating oil composition on the performance of the rotary engine when used for racing.

## 1. Lubricant for rotary racing engines

### 1.1 Oil supply system of a rotary engine used for racing

Fig. 1 shows the difference in the oil supply system between commercial rotary engines and the rotary engine designed for racing.

There are two lubricating parts of a rotary engine. One is the combustion chamber having sliding surfaces between the rotor housing and the seals, such as apex seals or side seals. The other is the engine system separate from the combustion chamber, which has gears and bearings such as the eccentric shaft.

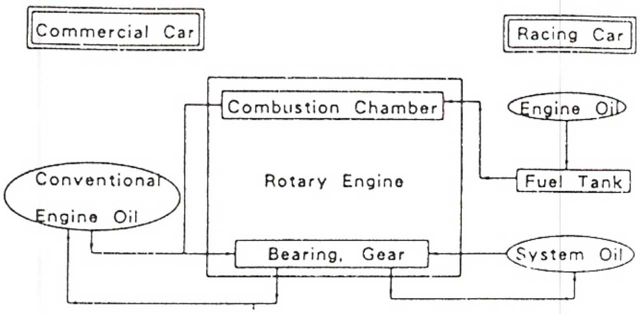


**Fig.1 Difference in Oil Supply Systems**

The commercial rotary engine has one oil tank. Oil is supplied to the engine, part of it being introduced into the combustion chamber. Therefore one oil serves as both the engine oil and the system oil.

On the other hand, the rotary engine used for racing has two oil tanks, which allow separation of the system and engine oils. The oil supply system for the system oil is the same as that for a commercial rotary engine. The engine oil is supplied to combustion chamber after mixing with the fuel in the fuel tank.

Mixing of the engine oil with the fuel is legally permitted for the racing car with rotary engine taking into consideration it's engine design.

### 1.2 Problem to be solved for rotary racing engine

One of the characteristic rotary engine problems is a "spitback". The rotary racing engine is continually exposed to severe operating conditions such as very high speed and full load during an endurance race. The rotary engine has three combustion chambers in one rotor.

The spitback phenomenon is the blow-through of burning gas from a chamber in the process of combustion to a chamber involved in the intake process[2]. It is considered to occur due to sticking of the apex seal. Spitback decreases the engine power output and increases the fuel consumption. Retarding the spark ignition timing is one of the counter-measures to avoid the spitback phenomenon, but this is not an appropriate way to solve this problem. Spitback is in fact protected by retarding the spark ignition timing from 25° to 20° before top dead center. However, the engine output torque decreases by about 2% by the retardation as shown in Fig. 2. Therefore the engine oil is required to have the capability of preventing the sticking of the apex seal at the same time providing good lubricity.

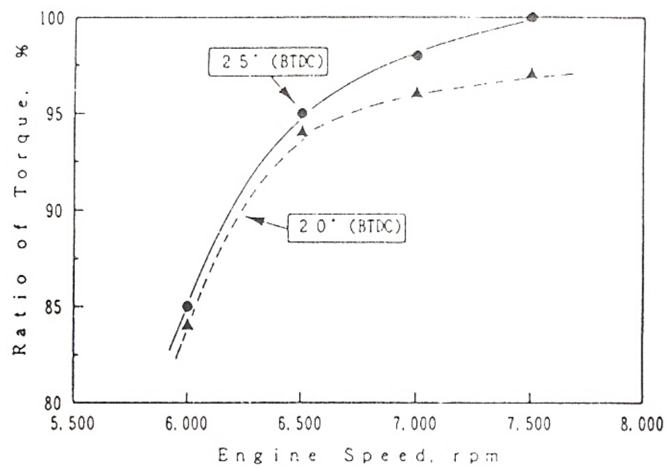


**Fig. 2 Influence of Spark Ignition Timing on Engine Output Torque**

The other problem is fuel consumption. An endurance race such as Le Mans has a regulation on the fuel amount used during the race. It is necessary for the system oil to have the capability of minimizing the fuel consumption without failure of the lubricated parts of the engine system outside combustion chamber.

## 2. Development of the engine oil

### 2.1 Performance requirements for an engine oil to prevent spitback

Lubricating conditions of the rotary racing engine combustion chamber is almost the same as that for 2 – cycle gasoline engine. However, the 2 – cycle gasoline engine has a capability to maintain engine power output, even if the top ring is stuck by the formation of carbonaceous deposits since conventional reciprocating engines have two piston rings to seal the combustion chamber. On the other hand, the combustion chamber of rotary engine is sealed by only one apex seal at apex of the rotor. Therefore the performance requirement for engine oil for rotary engine to avoid sticking is more important than that for 2 – cycle gasoline engine oil, as well as ratio of oil to fuel for rotary racing engine is decreased by about one half of that for 2 – cycle gasoline engine to reduce sticking. Explosion pressure and rotating speed are the predominant engine operating conditions controlling spitback. Spitback is not observed under the driving conditions used for commercial cars because their engine operating conditions are far from the regime of spitback. Fig. 3 shows a side view of the apex seal configuration at the apex of the rotor.

Spitback is observed when following equation is satisfied [3).

$$FP_0 + F > F_s + FP + F_{RA}$$

where $FP_0$ is the explosion pressure force, $F_s$ is the force of the spring installed between the base of apex seal groove and the apex seal, FP is the combustion gas pressure force applied on the back of apex seal by the explosion, $F_{RA}$ is radial acceleration force and F is frictional force. The clearance between the apex seal and the apex seal groove for the commercial rotary engine is in the range of several tens of $\mu$m. On the other hand, the clearance for the rotary racing engine has a tolerance close to near ten $\mu$m to increase engine efficiency. However, the frictional force is apt to increase due to the accumulation of carbonaceous materials between the apex seal groove and the apex seal. At the same time the combustion pressure force applied to the back of the apex seal is apt to decrease.

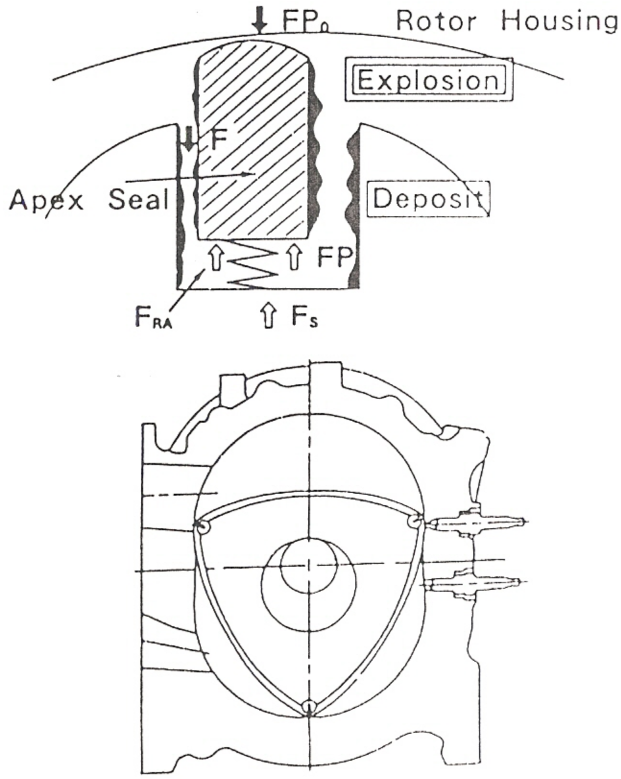


Fig. 3 Side View of Apex Seal

The characteristics of the engine oil used when spitback was observed during the endurance race is shown in Table 1. It is formulated using a mineral base stock and a conventional detergent inhibitor (DI) package for 4 – cycle gasoline engine oils. Carbonaceous deposits were observed around the apex seal groove, but not to a large extent. These deposits contained carbon and other materials attributed to the decomposition of the lubricant additives. Even though the amount of carbonaceous deposit was not large, spitback still occurred. Therefore, an engine oil is required which will not produce any carbonaceous deposits.

**Table 1 Physical & Chemical Properties of Reference Oil**

| | | |
|---|---|---|
| Viscosity, | 40℃ | 148 |
| mm²/s, | 100℃ | 14.9 |
| Viscosity Index | | 100 |
| TAN, mgKOH/g | | 2.87 |
| TBN, (D2896) | | 5.64 |
| Sulfated Ash, %wt | | 0.87 |
| Carbon Residue, %wt | | 1.07 |

## 2.2 Influence of engine oil composition on deposit formation

### 2.2.1 Results of laboratory tests

It is known that the surface temperature of the apex seal groove is in the range of 240℃ to 280℃ (from the results of in-house engine tests simulating the driving conditions of Le Mans). In order to evaluate the influence of base oil composition, it's viscosity, and the treat rate of the DI package on carbonaceous deposit formation, thin oil film coker tests were conducted using twelve different oil samples as well as the engine oil described in Table 1 as a reference oil.

Test conditions were as follows:

Sampling : 100mg in a 50cc glass beaker (this gave about 100 μm oil film thickness)

Atmosphere : air

Test temperature : 280℃

Test duration : 10 hours

Test results are summarized in Table 2. Fig. 4 shows that the chemical composition of the base oil noticeably influences the formation of the carbonaceous deposit. The lowest amount of the deposit was found using polybutene as opposed to mineral base stock, polyalphaolefin and polyolester. Also, carbonaceous deposit was found to increase with the increase of the base oil viscosity.

**Table 2 Results of Thin Oil Film Coker Test**

| Test Oils | Viscosity 100℃ mm²/s | Residue %wt |
|---|---|---|
| Ref. Oil | 14.9 | 33.2 |
| ① Mineral Oil 100N | 4.0 | 10.6 |
| ② Mineral Oil 150N | 5.5 | 12.8 |
| ③ Mineral Oil 500N | 10.8 | 30.3 |
| ④ Polyalphaolefin | 4.0 | 15.5 |
| ⑤ Polyalphaolefin | 6.0 | 25.2 |
| ⑥ Polybutene - ⓐ | 4.5 | 2.1 |
| ⑦ Polybutene - ⓑ | 10.5 | 2.6 |
| ⑧ Polybutene - ⓒ | 32.4 | 3.7 |
| ⑨ Polyolester | 4.4 | 59.5 |
| ⑩ ②+ DI (4%wt) | 5.6 | 14.5 |
| ⑪ ②+ DI (8%wt) | 5.9 | 16.2 |
| ⑫ ③+ DI (4%wt) | 10.9 | 32.4 |

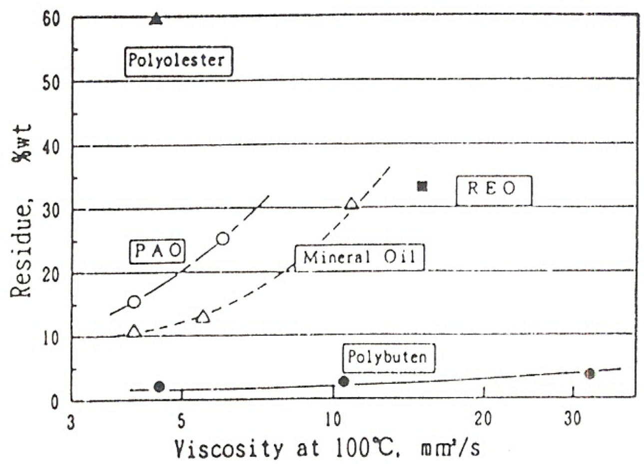


**Fig. 4 Influence of Base Oil Composition on Carbonaceous Deposit Formation**

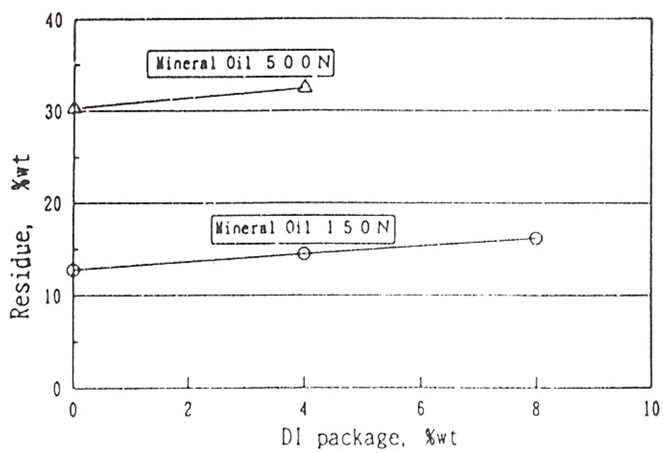


**Fig. 5 Influence of DI package on Carbonaceous Deposit Formation**

Fig. 5 indicates that the increase of the additive treat rate does not decrease the carbonaceous deposit.

### 2.2.2 Results of in – house engine tests

Based on the results of the thin oil film coker tests described above, five engine oil samples were formulated for in – house engine tests in order to clarify the influence of the engine oil composition on the formation of the carbonaceous deposit and the generation of the spitback phenomenon. The spitback was evaluated measuring the change of engine output torque as shown in Fig.6. The change of engine noise and the occurrence of backfire in the carburetor were simultaneously observed to confirm the generation of spitback.

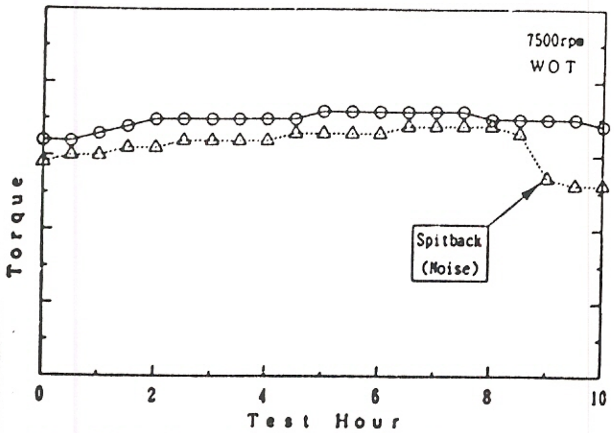


**Fig. 6 Relationship between Spitback and Change of Torque**

**Table 3 Formulation and Characteristics of Engine Oil Samples**

| Items | Ref.Oil | A | B | C | D | E |
|---|---|---|---|---|---|---|
| Base Oil | MO | PES | PAO | PB | PB | PB |
| DI(Metallic,Ashless) | M,A | M,A | M,A | M,A | A | M,A |
| Viscosity 100 ℃ mm²/s | 14.9 | 21.2 | 6.1 | 9.9 | 10.0 | 10.0 |
| Sulfated Ash,% wt | 0.84 | 0.16 | 0.08 | 0.08 | 0.01 | 0.40 |
| TFC.Residue, % wt | 33.2 | 55.3 | 25.6 | 5.4 | 5.2 | 7.8 |

MO : Mineral Oil, PES : Polyolester

PAO : Polyalphaolefin, PB : Polybutene

Table 3 summarizes the formulation and some characteristics of these engine oil samples. The operating conditions for the in – house engine test are shown in Table 4. These were established to simulate the driving condition of Le Mans. However, leaded gasoline was not used as a fuel in order to avoid the influence of gasoline additives on the formation of the carbonaceous deposit. The characteristics of the unleaded gasoline used for the in – house engine test are shown in Table 5.

**Table 4 In-house Engine Test Condition for Evaluation of Cabon aceous Deposit and Spitback**

| | |
|---|---|
| NO. of Rotor | 1 |
| Engine Displacement , cc | 654 |
| Engine Speed rpm | 7500 |
| Ignition Timing , ° (BTDC) | 25 |
| Oil Temperature , ℃ | 80 |
| Load | WOT |
| Test Duration , h | 10 |

Fuel : Unleaded Gasoline, System Oil : SAE40,SG

**Table 5 Physical & Chemical Properties of Fuel**

| | |
|---|---|
| Density kg/m³ , 15 ℃ | 754 |
| Octane NO. , (F – 1) | 100 |
| Aromatics, % vol | 41 |
| Olefin HCs., % vol | 20 |
| Saturated HCs., % vol | 39 |

Test results are summarized in Table 6 together with the results of the thin oil film coker tests.The following conclusions were drawn from the in – house engine tests. In terms of the formation of the carbonaceous deposits good correlation was observed between the thin oil film coker test and the in – house engine test. Also, spitback phenomenon was found to have a relationship with the formation of the carbonaceous deposit. Spitback phenomenon can be improved by decreasing the amount of the carbonaceous deposit.

**Table 6 Results of In-house Engine Test for Carbonaceous Deposit**

| Items | REO | A | B | C | D | E |
|---|---|---|---|---|---|---|
| Base Oil | MO | PES | PAO | PB | PB | PB |
| TFC. Residue % wt | 33.2 | 55.3 | 25.6 | 5.4 | 5.2 | 7.8 |
| Carbon Filling of Apex Seal Groove[1] | 5 | 0 | 6 | 9.5 | 8 | 7 |
| Spitback[2] | Light | Heavy | None | None | None | None |

1) 10 : Clean, 0 : 20 % < , 2) Noise, Change of Torque

TFC : Thin Oil Film Coker Test

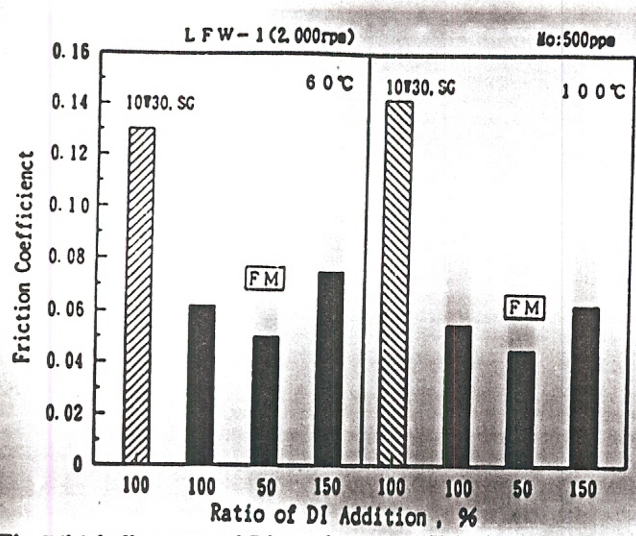


**Fig.7(b) Influence of DI package on Friction Characteristics of Organic Molybdenum Compound**

Table 7 shows the characteristics of system oil previously used for Le Mans. Cars racing at Le Mans cover about 4500 km during 24 hours. The increase of the TAN of the system oil for a rotary engine is smaller than that for a 4 – cycle gasoline engine oil at about the same mileage of 4500 km.

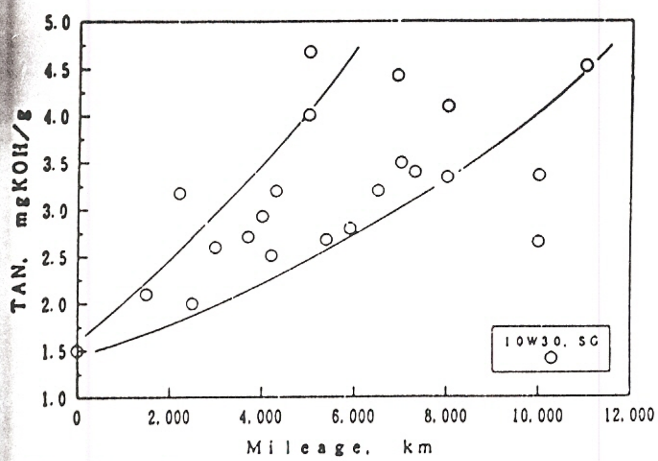


**Fig.8 Used Oil Analysis of Conventional 4 – cycle Gasoline Engine Oil**

**Table 7 Used Oil Analysis**

| Items | New Oil<br>– | Used Oil<br>4500km |
|---|---|---|
| Viscosity 40℃ | 148 | 138 |
| mm²/s, 100℃ | 14.9 | 14.6 |
| TAN, mgKOH/g | 2.87 | 2.89 |
| Insolubles %wt | – | 0.08 |
| Fuel Dilut %wt | – | 0.9 |

Lubricating condition of the system oil is not so severe as that of 4 – cycle gasoline engine oil since the engine system of rotary engine is separated from the combustion chamber. Therefore, it is also possible to decrease the treat of the DI package and still maintain the oxidation stability for the system oil.

### 3.3 Results of in – house engine tests

System oil samples for in – house engine test were formulated using polyalphaolefin as the base oil, an organic molybdenum compound as friction modifier and a small amount of an API SG engine oil DI package. Viscosity grades of these samples ranged from SAE 20 to SAE 40. Sample C described in Table 3 was used as an engine oil for the combustion chamber.

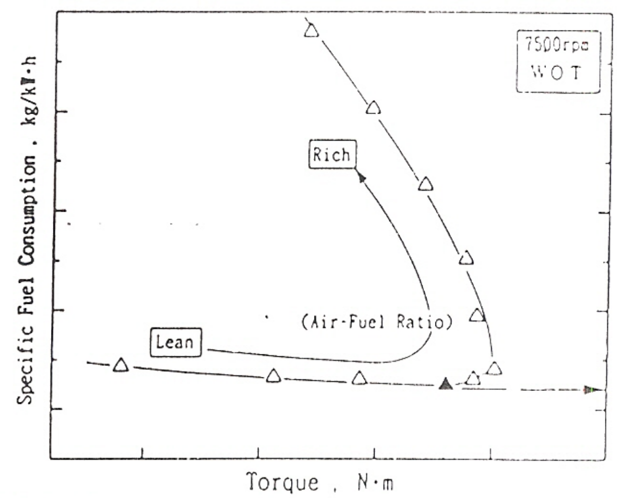


**Fig.9 Measurement of Specific Fuel Consumption**

The fuel consumption was measured by varying the air – fuel ratio nearby the theoretical air – fuel ratio after the engine had been operated for 10 hours in accordance with the test conditions described in Table 4. The optimum specific fuel consumption was the minimum value on the curve relating specific fuel consumption with air – fuel ratio as shown in Fig. 9. The fuel saving ratio of system oil samples to the reference oil, which is the same as described in Table 1, was calculated using the minimum value.

Test results were summarized in Table 8

surface temperature reaches 150℃ by 3 to 4℃. The engine inlet temperature of system oil is controlled at 80℃ by a cooler during the endurance race. This work indicates that the addition of an organic molybdenum compound makes it possible to lower the surface temperature of the bearing metal in the engine system to a significant extent under the operating conditions of endurance races.

## 4. Summary and conclusions

The summary and conclusions obtained in the development of a lubricating oil for rotary racing engines are as follows :

### 4.1 Engine oil for the combustion chamber

(1) The spitback phenomenon is improved by a decrease of the carbonaceous deposit and ash produced in the apex seal groove.

(2) The chemical composition of the base stock predominantly influences the formation of the carbonaceous deposit.

(3) The least amount of deposit formation can be achieved using polybutene as base stock, in comparison with mineral base stock, polyalphaolefin and polyolester.

(4) Increase of DI package does not decrease the carbonaceous deposit.

### 4.2 System oil for engine system outside combustion chamber

(1) Lower base oil viscosity contributes to improved fuel consumption. However, from the view point of prevention of failure of the bearing surface, it is necessary to use a base stock having a viscosity grade over SAE 40.

(2) Addition of organic molybdenum compound as friction modifier is expected to improve fuel consumption by 1 to 1.5% and lower the surface temperature of the bearing metal by a significant amount.

(3) Addition of a large amount of DI package adversely affects the fuel saving achieved by adding an organic molybdenum compound.

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