Importance of Railroad Diesel Engine Oil TBN and its Relevance to LMOA Generation 5 for Salicylate Oils©

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A railroad lubricant possesses alkalinity, expressed as total base number (TBN), to neutralize acids that are formed in service. The two widely accepted methods for measuring TBN of an oil are ASTM D2896 and D664. The difference between these two methods is highlighted in terms of what they actually measure, and their relative merits for fresh and used oils. The importance of TBN retention is illustrated with laboratory oxidation and bench engine test data where a benefit is seen for oils based on the salicylate detergent system compared to oils based on other detergents. In the context of the recently defined LMOA Generation 5, TBN depletion and other used oil data from the field are discussed for salicylate-based 13 and 17 TBN oils. The impact of LMOA Generation 5 requirements on fresh oil TBN is considered.

INTRODUCTION

Lubricant alkalinity or base is one of the key factors which govern oil life in medium- and high-speed diesel engines. A crankcase lubricant possesses alkalinity, expressed as total base number (TBN), in order to neutralize acids formed during normal engine operation. A crankcase oil must maintain an adequate level of TBN during service to prevent the build up of acids. Failure to control acid levels will lead to excessive engine deposits and, more importantly, corrosive attack of engine components such as cylinder liners, piston rings, and bearings. Hence, TBN is frequently monitored in automotive and locomotive applications in order to signal when the lubricant base level falls below a minimum level and the oil needs to be changed. An adequate level of used oil TBN is particularly important in railroad applications where increasing stress is being placed on the oil by trends in engine design (1) to higher power outputs and lower oil consumption, and by the operational requirement, defined by Locomotive Maintenance Officers Association (LMOA) Generation 5 (2), to extend the oil drain interval to 180 days.

In the above context, this paper addresses three topics:

1. To consider in general terms what constitutes lubricant base, expressed as TBN.
2. To briefly compare and contrast how oils based on different chemistries compare in their TBN retention characteristics in railroad bench tests.
3. To consider the impact of LMOA Generation 5 requirements on fresh oil TBN. This part of the paper will draw upon the author's field experience with salicylate-based oils.

LUBRICANT BASE (TBN)

What is Lubricant Base?

The major source of base in a lubricant is the metal-containing detergent additive. This additive commonly contains calcium and is termed "overbased" because it comprises a central inorganic core of basic calcium carbonate/hydroxide which is kept in colloidal suspension in the lubricant by detergent soap molecules. These soap molecules are generally one of three types: calcium salicylate, calcium sulphonate or calcium phenate. A typical overbased detergent additive is shown schematically in Fig. 1. The inorganic core of this additive is primarily responsible for neutralizing the two types of acids that appear as contaminants in the lubricant: 1) inorganic acids, such as sulfuric, sulfurous and nitric acids from fuel/air combustion plus a very low concentration of hydrochloric acid from partial decomposition of the lubricity additive, and 2) organic (carboxylic) acids from oil and fuel oxidation. TBN will be depleted by these two routes.

Lubricant TBN can also have contributions from detergent soap molecules (in the case of salicylate and phenate, though not sulfonate soap) and from the basic nitrogen-containing dispersants. Other railroad oil additives, depending on their structure, may also contribute to the measured TBN. The major role of detergent soap molecules, as their name implies, is to keep engine components such as pistons and rings clean. This function occurs through the surfactant properties of soap molecules.

Determination of TBN

The principal methods for measuring oil TBN in engine oils are ASTM D2896 (3) and D664 (4). A comparison of these two plus the more recent D4739 method is shown in Table 1(a). Although the ASTM have nominally replaced the D664 method by D4739 (the “trisolvent” method), acceptance of the latter method by the industry has been slow, in part because it uses the relatively toxic solvent chloroform. The ASTM have assessed less toxic solvents and a revised method for D4739 is expected in 1991. At the present time D2896 and D664 remain as the two principal methods for measuring oil TBN.

Fresh oil TBN and residual TBN in a used oil are measured by reacting the oil with a particular acid. Anything more basic than the acid used in the method will be measured as base. An essential difference between the D2896 and D664 methods is the acid used; D2896 uses perchloric acid, which is stronger than the hydrochloric acid used in D664. For fresh oils, this change in acid plays a relatively small role and only small differences are seen for TBN as measured by the two methods, with the D2896 method consistently giving the higher values. At the author’s laboratory, differences of typically 0.3 to 1.5 units have been observed between the two methods for commercial railroad oils with the larger differences being seen for 17 TBN(D2896) oils. Since the D2986 method measures all the base in a fresh oil and has the better precision of the two, it is the generally preferred method for fresh oils.

For used oils, however, the change in acid between D2896 and D664 has a major effect. The stronger acid in D2896 measures both lubricant basic components and lubricant degradation salts such as metal formats and acetates. In contrast, the D664 method, with its weaker acid, has little tendency to measure these products. These effects have been confirmed by experiments performed at the author’s company. These results are summarized in Table 1(b). Table 1(b) shows that calcium salts of oxidation acids (formic, acetic and stearic acids) provide a significant contribution to TBN as measured by the D2896 method, but not to TBN D664. Interestingly, Table 1(b) also shows that calcium nitrate is measured by D2896 but not by D664, however iron(III) nitrate is not measured by either method. Thus these data indicate that nitrates can interfere with the D2896 method for used oils, and that predicting this interference is not straightforward. An important message from this work is that none of the products listed in Table 1(b) play a useful role in controlling levels of acids in used oils because they will react with a strong acid such as sulfuric acid to release other acids. Thus these degradation salts will not control the overall concentration of acids. Table 1(b) helps to explain why:

1. TBN values of used oils by D2896 are always higher than those by D664. Reliance on the D2896 method can lead to a false sense of security and can fail to indicate when useful base is depleted.
2. Technically, the D664 method is recommended for used oils because it measures useful base. This recommendation stands in spite of the repeatability of the D664 method being worse than that of the D2896 method.

The TBN(D4739) measurements summarized in Table 1(b) indicate that this method lies somewhere between the other two in its tendency to measure degradation salts. This fits in with the author's experience of D4739 measurements of used railroad oils from the field which have consistently fallen between D2896 and D664 values.

In light of the above, TBN changes measured in bench tests and from the field, discussed in the rest of the paper, will refer to the TBN(D664) method.

TBN RETENTION AND LUBRICANT CHEMISTRY

As indicated earlier, organic acids from oil oxidation contribute to TBN losses observed in service. This important element of TBN loss can be simulated by suitable bench oxidation tests and these can therefore be used to screen for field performance.

In a previous paper (5), the author discussed TBN retention in the EMD LO.201-47 (6), General Electric (7), and Union Pacific (UP) oxidation (8) tests and in the Caterpillar IG-2 (480 hour) high-speed diesel engine test (9). In these experiments it was demonstrated that detergent chemistry affects the rate of TBN depletion. Table 2 summarizes the data generated in these tests. In all four screening tests, the oils based on the salicylate detergent system consistently

TABLE 1(A)-ASTM TBN METHODS: WHAT DO THEY MEASURE?

	D2986	D664	D4739
ACID	Perchloric in glacial acetic acid	Alcholic HCI	Alcoholic HCI
SOLVENT	Chlorobenzene/glacial acetic acid	Toluene/IPA /water	Tolueue/IPA /chloroform
MEASURES	· Strong bases · Weak bases	· Strong bases · Only some weak bases	· Strong bases · Only some weak bases
EXAMPLES FRESH OIL	· All detergent base · All dispersant (amine) base	· All detergent base · Most dispersant base	· All detergent base · Most dispersant base
EXAMPLES USED OIL	· Most Ca, Mg salts of degradation products*	· Very few Ca, Mg salts of degradation products	· Some Ca, Mg salts of degradation products*

*Refer to Table 1(b)

TABLE 1(B)-TBN of Used Oil Degradation Products*

DEGRADATION PRODUCT	D2896	D664	D4739
Ca formate^{+}	⚐	X	X
Ca acetate^{+}	⚐⚐⚐	⚐	⚐⚐
Ca stearate^{+}	⚐⚐	X	⚐⚐
Cu(II) acetate^{++}	X	X	X
Ca sulphate^{++}	X	X	X
Fe(III) sulphate^{++}	X	X	X
Cu(II) sulphate^{++}	X	X	X
Ca nitrate^{+}	⚐⚐	X	X
Fe(III) nitrate^{++}	X	X	X

Method Model degradation products were obtained analytically pure from chemical suppliers. They were mixed at 1% with 3 fresh. LMOA-type railroad oils of 17 TBN (D2896). The 3 oils were based on salicylate phenate and phenate/sulphonate detergent systems. TBN. D2896. D664 and D4739 were measured on the formulations before and after addition of the compounds. Duplicate measurements were made.

Results ⚐ corresponds to a <1 unit boost ⚐⚐ to a 2-3 unit boost ⚐⚐⚐ to a 6-7 unit boost to a 17 TBN (D2896 oil. Only small oil-to-oil differences in boosts were observed.
X = No boost observed.

*These results show that predicting which compound is measured by D2896 is not straightforward: theory might predict that Cu(II) acetate is measurable whereas calcium nitrate is not. In fact the reverse is true.
$^{+}$ = anhydrous. $^{++}$ = contains water of crystallization.

showed lower TBN (D664) losses (i.e. better TBN retention) than oils based on other detergent chemistries and this was found to be true at both the 13 and 17 TBN levels. Importantly, other oil properties were also controlled in these tests. Examination of TBN losses with time in the UP oxidation test is informative because these plots (shown in Fig. 2) show that the salicylate oils lose TBN (D664) at a lower rate compared to oils based on alternative detergent chemistries, and that interestingly, the 13 TBN oil based on salicylate chemistry ended up with a higher retained TBN at the end of test compared to a 17 TBN oil with different detergent chemistry.

One of the reasons why salicylate oils show an advantage in TBN retention over some other detergent systems lies in the structure of the salicylate molecule (shown in Fig. 1) and its antioxidant properties. The antioxidant capability of this structure arises largely from the hindered pheno group which traps free radicals from oxidation. This will lead directly to lower concentrations of hydroperoxides (ROOH) and therefore to lower levels of organic acids. Thus there will be less acid neutralization of the inorganic base of the detergent additive and better TBN retention. In summary, the benefit in TBN retention for salicylate oils is linked to their good oxidation control.

TBN AND LMOA GENERATION 5

In this section field performance of 13 and 17 TBN oils (salicylate type) in GE and EMD locomotives is summarized in relation to targets for LMOA Generation 5, as defined at LMOA 1989 (2). The field trials discussed were carried out according to LMOA guidelines.

TABLE 2 – TBN (D664) LOSSES FOR 13 AND 17 TBN RAILROAD OILS*

			TBN LOSS, mg Koh g^{-1}			
OIL*	LMOA	TBN	EMD LO.201-47 (325 F)	GE Oxid.	UP Oxid.	CAT** Ig2
A_1	5^+	13	2.4	1.2	4.7	4.2
B_1	4	13	3.4	2.3	7.6	7.1
C	4	13	2.6	2.9	10.5	6.6
D	4	13	3.0	2.6	8.5	5.9
A_2	5^+	17	1.8	1.5	6.5	3.3
B_2	5^+	17	4.7	4.5	10.9	7.4

*Oxidation test results are based on mean values of between two and six data points. The CAT 1G2 data are single data points apart from the value shown for A_1 which is a mean of two results.
*A = salicylate based railroad oils.
B,C,D= other commercial railroad oils.
**mean of four 120 hr. oil samples, the sump charged having been changed every 120 hours.
$^+$As assessed from held trial data, relative to LMOA Gen. 5 criteria. Note that TBN is not specified in current definition of LMOA Generation 5.

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Fig. 2 – Union Pacific oxidation test data fro MVI blends.

17 TBN (Salicylate Oil Performance in GE Locomotives

GE Dash 8 locomotives place considerable stress on the crankcase oil through a combination of high power output and low oil top-up resulting from low oil consumption. Thus this type of locomotive represents a severe test of the lubricant and will set a lower limit on the oil's useful lifetime.

A 17 TBN oil of SAE 40 viscosity grade and formulated with salicylate chemistry in HVI basestock has been evaluated in four GE C39-8 locomotives involved in heavy duty coal train service. As reference, five locomotives of the same type ran on a commercial 17 TBN oil based on different chemistry and using MVI basestock. Table 3 shows the key features of the trial. Although accurate oil consumption data was not available, the railroad estimated oil consumption to be similar for both test and reference units.

During the trial, used oil condition was monitored relative to limits to viscosity at 210 F (30 percent increase), coagulated pentane insolubles (5 percent) and TBN (D664) (o.5). The oil based on salicylate chemistry showed:

1. Used oil condition remained within all of the above condemnation limits for well beyond 400 days (see used oil data in Figs. 3-5). The crankcase oil was changed for the test locomotives between 412 and 441

TABLE 3-17 TBN TRIAL WITH GE LOCOMOTIVES – KEY FEATURES

OIL : 17 TBN, SAE 40 (HVI), salicylate-based
LOCOMOTIVES : 4 x GE C39-8
SERVICE : Heavy Duty Coal Train
DURATION* : 12 Months
MILEAGE* : 82-91,000
OIL CONSUMPTION : Accurate data not available

*The end of trial inspection was performed at 12 months, corresponding to between 82 and 91,000 miles. The demonstrated crankcase oil life was longer than this period, being between 412 and 441 days.

INSERT FIGURE 3 GRAPH HERE

Fig. 3 – TBN (D864) with time for GE C39-8 units.

INSERT FIGURE 4 GRAPH HERE

Fig. 4 – TBN (D864 with time for GE C-39-8 units.

INSERT FIGURE 5 GRAPH HERE

Fig. 5 – Viscosity at 210 F with time for GE C39-8 units. *

*Curve obtained by fitting data to function
VIS=A + B (1- ???).

days due to the test oil having run out, not because of a condemnation limit having been reached.

2. A high level of base reserve was achieved and this is illustrated in Fig. 3 where TBN (D664) is plotted against oil service days, the time of operation actually experienced by the oil drain. These data have been fitted to an exponential function (shown as the full line in Fig. 3) which shows the average change of TBN with time and gives the average equilibrium level of TBN as 3.3 units. This level of base reserve was well above the 1.0 limit set for Generation 5 and was also higher than the equilibrium level determined for the reference oil which averaged at 1.5 units (Figs. 3 and 4). This benefit was found to be statistically significant at greater than the 99 percent level of confidence. Further details on the statistical analysis of TBN data from this trial, including how the equilibrium levels of TBN were calculated, are contained in the Appendix.
3. Good control of viscosity increase and insolubles was demonstrated for beyond 400 days. Viscosity showed a distinct plateauing off at about 18cSt. Relative to the condemnation limit of 19.6cSt. 30 percent over the fresh oil value (Fig. 5). This implied that levels of oxidation were low and under control during this extended drain, and this was confirmed by low levels of carbonyl absorption measured in used oils by Differential Infrared (DIR) spectroscopy. Levels of coagulated pentane insolubles remained below 2.5%w.
4. Wear metal concentrations (iron, copper and lead) were low, indicating low rates of engine component wear.

At the end of 12 months, detailed inspections of the engines run on the salicylate oil showed very satisfactory control of engine deposits. Levels of sludge deposits measured in the valve deck and crankcase areas were low with ratings (using CRC Manual 12 procedure) between 9.5 and 9.8 obtained at the end of 12 months relative to 10 for clean. Low levels of both power assembly deposits and of engine component wear were also measured at the inspection. In summary, the 17 TBN oil with HVI basestocks (salicylate chemistry) achieved an extended drain of greater than 12 months in heavy-duty operation while maintaining control of engine deposits and wear. This performance exceeds the required for LMOA Generation 5.

13 TBN (Salicylate Chemistry) Oil Performance in GE Locomotives

GE Dash 8 locomotives have also been used to evaluate the performance of a salicylate-based oil at the 13 TBN level in a test with eighteen C40-8 locomotives. The oil was SAE 40 viscosity grade and formulated with MVI basestock. During 13-month period five of the eighteen locomotives had an oil drain change to a commercial 17 TBN oil based on a different chemistry and this provided an opportunity to compare performance of the two oils for these locomotives. Table 4 summarizes the key elements of the field evaluation, in terms of mileage accumulation and type of service and age of locomotives. Oil consumption data is one useful factor in deciding the level of stress experienced by the oil; in this instance, however, an accurate record of oil consumed was not available. This situation is to a large extent counterbalanced by the fact that (a) new or relatively new Dash 8 locomotives were used in this test and were powered by relatively low oil-consuming engines; (b) a very large population of locomotives is considered adding significance to any conclusions drawn; and (c) high oil stress will arise from the very high utilization during the test. Mileage accumulated for the eighteen locomotives was very high, ranging from 143,000 to 179,000 miles per year, which exceeds that required for LMOA Generation 5.

An initial examination of the used oil data suggested that there was some influence of mileage accumulation on oil properties and the data broadly fell into two groups, greater than 154,000 miles per year, and less than 154,000 miles per year. Further analysis of the used oil data is in progress and the results from this will be published at a later date.

Figures 6(a) and (b) show plots of viscosity at 100 C with oil for the low and high mileage locomotives respectively, demonstrating that in both cases viscosity increase was controlled within the Generation 5 limit of 30 percent for beyond 180 days. Not surprisingly perhaps, the higher mileage locomotive data show a distinctly more severe trend in oil thickening, Fig. 6(b); however, these data still demonstrate oil life in excess of 200 days. A noticeably wider spread of the data compared to that of the 17 TBN oil (see Fig. 5) is undoubtedly due to the large number of locomotives involved for the 13 TBN oil.

Plots of TBN (D664) with time for the low and high mileage sets are shown in Figs. 7(a) and (b) respectively.

TABLE 4 – 13 TBN TRIAL WITH GE LOCOMOTIVES
KEY FEATURES

OIL	:	13 TBN, SAE 40 (MVI), salicylate-based
LOCOMOTIVES	:	18 x GE C40-8
LOCOMOTIVE AGE AT START	:	2-14 months
SERVICE	:	Mixed, Heavy Duty Freight and High Speed Service
DURATION	:	Up to 13 Months
MILEAGE PER YEAR	:	149-179,000
OIL CONSUMPTION	:	Accurate data not available

INSERT GRAPHS (A) AND (B) HERE

Fig. 6(a) – Viscosity vs. oil days for 8x GE C40-8 units with lower mileage.
Fig. 6(b) – Viscosity vs. oil days for 10x GE C40-8 units with higher mileage.

INSERT FIGURE (A) AND (B)

Fig. 7(a) – TBN D684 vs. oil days for 8x GE C40-8 units with lower mileaged.
Fig. 7(b)-TBN D684 vs. oil days for 10% GE C40-8 units with higher mileage.

These demonstrate good base retention for the 18 locomotives for beyond 180 days, and above the Generation 5 limit of 1.0 units. There was a relatively wide spread in residual base in the used oil at 200 days, which varied between about 1 and 6 units. In summary, good viscosity-increase control and TBN retention are demonstrated by the 13 TBN oil, both properties remaining within LMOA Generation 5 field test limits. In addition, based on the five locomotives indicated above, the salicylate-based 13 TBN oil showed similar or better control of oil properties compared to the other commercial 17 TBN oil.

Close comparisons of oil performance across different railroad operations require caution because a number of factors are likely to change. Within this reservation for salicylate oil performance data, control of viscosity increase for the low mileage accumulating locomotives on the 13 TBN oil, Fig. 6(a), was comparable to that demonstrated by locomotives operating on the 17 TBN oil, Fig. 5. However, control of viscosity increase shown by the 13 TBN oil with the high mileage locomotives, Fig. 6(b), was not as good but it still met LMOA Generation 5 targets.

Detailed inspections were made on three locomotive engines (and test power assemblies) which had run on the 13 TBN oil (salicylate chemistry) for approximately 13 months, following an initial period from new (3 to 5 months) with the factory fill oil. Each locomotive had experienced extended oil drains of greater than 180 days. These inspections showed satisfactory engine cleanliness (engine sludge rating by CRC Manual 12 of between 8.8 and 9.6 relative to 10.0 for clean) and low rates of component wear, in both cases equivalent to levels expected for shorter oil drain intervals. This has demonstrated that the 13 TBN oil based on salicylate chemistry also meets the criteria of LMOA Generation 5 performance.

13 and 17 TBN (Salicylate Chemistry) Oil Performance in EMD Locomotives

Because EMD two cycle engines have higher oil consumption, and therefore higher oil top-up rates compared to GE engines of recent three-ring piston design, they consequently put less stress on the lubricant. Two oils of 20W40 viscosity grade and formulated to 17 and 13 TBN with the same salicylate chemistry used in the GE trials discussed above have been field tested in EMD locomotives for one and two years, respectively. The locomotives were powered by 645-turbocharged engines. Table 5 summarizes the key elements of the trials in terms of the type and number of locomotives involved, type of duty and mileage accumulated. Figures 8(a) and (b) show TBN (D664) plotted against oil days for the two trials. The 13 TBN trial ran for almost two years and oil showed excellent TBN retention, an equilibrium value for TBN being recorded at approximately 6.0 which is well above the EMD condemnation limit of 0.5 as shown in Fig. 8(b). in the 17 TBN trial oil TBN equilibrated at an even higher level, at approximately 9.0

TABLE 5-13 TBN AND 17 TBN EMD FIELD TRIALS
KEY FEATURES

	OILS (SALICYCLATE-BASE)	
	13 TBN, 20W40	17 TBN, 20W40
· LOCOMOTIVES (Engine Type)	1 x GP 40 1 x GP 40-2 (645 turbocharged)	2 x SD 40 2 x SD 40-2 (645 turbocharged)
· SERVICE	General freight and high speed intermodal (container)	Coal Train
· DURATION	24 Months	13 Months

· MILEAGE, OVERALL	128-156,000	129-132,000

Fig. 8(b), indicating that there was little stress on this parameter. In both these trials control of other used oil properties such as viscosity, pentane insolubles, and wear metals was good. Engine inspections carried out at the end of each trial showed that in each case levels of engine deposits and component wear, including the silver wrist pin bearing, were low.

SUMMARY

Experience with 13 and 17 TBN railroad oils based on salicylate chemistry shows that they more than adequately lubricate EMD engines in the field. In addition, the two oils demonstrate LMOA Generation 5 quality, as judged by their field performance in the GE Dash 8 engine. It is notable that the 13 TBN oil comfortably meets the particularly stringent performance requirements of GE Dash 8 engines in high mileage/general freight service. The oil drain interval demonstrated in this case is, at greater than six months, in line with maintenance practices of U.S. railroad operators.

Looking to future requirements for railroad crankcase oils in North America, the levels of sulphur in diesel fuels are very likely to fall, possibly to the 0.05%w level, and this will have an impact on the requirement for fresh oil TBN. Although there will clearly need to be a minimum level of fresh oil TBN, the field performance data on salicylate-based oils indicates that 17 TBN is likely to exceed this minimum level and that a lower TBN level would more effectively lubricate medium-speed locomotive engines.

CONCLUSIONS

1. The two widely used methods of measuring base in used oils, ASTM D2896 and D664, the D664 method is technically preferred because it only measures effective base.
2. Commercial LMOA-type railroad oils based on different detergent chemistries demonstrate differences in TBN retention as measured in industry screening tests including both laboratory oxidation and bench engine tests. Oils based on the salicylate system show better TBN retention compared to other commercial oils.

INSERT GRAPH 8(a) AND (b) HERE

Fig. 8(a) – TBN (D684 with time for EMD S(40/40-2 units.
Fig. 8(b) – TBN (D684) with time for EMD GP 40/40-2 units.

3. Thirteen and 17 TBN railroad oils based on salicylate chemistry demonstrate satisfactory field performance as measured both in EMD locomotives with 645-turbocharged engines and in GE Dash 8 locomotives. GE field experience was gained

through (1) heavy duty coal service for the 17 TBN/HVI oil and (2) general freight service with very high utilization for the 13 TBN/MVI oil. In both cases the oils achieved extended oil drain intervals without compromising levels of engine deposits and engine wear. Thus the two oils demonstrated field performance at the LMOA Generation 5 level.

4. The 13 TBN railroad oil based on salicylate chemistry provides a oil drain interval of greater than six months with GE locomotives operating in high mileage/general freight service. This oil drain interval is in line with maintenance practices of U.S. railroad operators.

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