High Thermal Stress Turbine Oil Specifications for Modern Gas Turbines

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Abstract

The specifications for high thermal stress turbine oils for modern gas turbines have evolved significantly over the years. With the increasing power output and efficiency of large gas turbines, the demands on turbine oils have also risen. This document discusses the development of specialized oxidation tests to ensure the performance and long-term stability of these lubricating oils under demanding conditions such as with gas turbines. Historical tests laid the foundation for evaluating oxidation stability, while modern tests like the RPVOT and Dry TOST test have further refined the assessment process. The introduction of the third generation of turbine oils, tested against varnish formation, highlights the need to incorporate contemporary requirements into standards. In addition, this paper discusses the selection of an appropriate turbine oil and how to ensure long-term stability.

1. Introduction

Over the years, there has been a steady increase in the power output and efficiency of large gas turbines.
This has had an impact on the demands placed on the turbine oils used. These have improved considerably over the last few decades to ensure that the turbines continue to operate trouble-free. In particular, oil chemical processes during operation have accelerated due to increased bearing temperatures and load factors. Specially adapted oxidation tests had to be developed to ensure and predict the performance and long-term stability of these lubricating oils under particularly demanding thermal and oxidative conditions.

2. General requirements for oxidation tests

Lubricant aging is a function of temperature and other parameters. These ageing tests are performed on fully formulated products. They are used to evaluate the quality of the oil and its suitability for the application. The various oxidative stability tests are the most commonly used methods for testing the ageing properties of lubricants. Standardized test methods with test times ranging from hours to months are available.
The majority of these tests are based on exposing test fluids to oxygen or air at relatively high temperatures in the presence of catalyst metals. This is done to increase oxidation rates and reduce test duration.
Oxidation stability is evaluated by the qualitative and quantitative determination of oxidation products, oxygen uptake, changes in viscosity, and changes in acidity or sludge and varnish formation.

3. Early Oxidation Tests

In the early days, oxidation tests for turbine oils were relatively simple and focused on measuring the oil's resistance to oxidation under controlled conditions.

3.1. Baader oxidation test (former DIN 51554)

The Baader oxidation test was first published in 1928 and is named after the German chemist Dr. Baader. Figure. 1 shows the historical test equipment. The test was developed to evaluate the ageing resistance of lubricating oils under controlled conditions. The Baader oxidation test is an important milestone in the history of lubricating oil testing as it provides a standardized method for evaluating the oxidation stability of oils. The test was further developed and refined over the following decades to meet changing requirements and technologies.

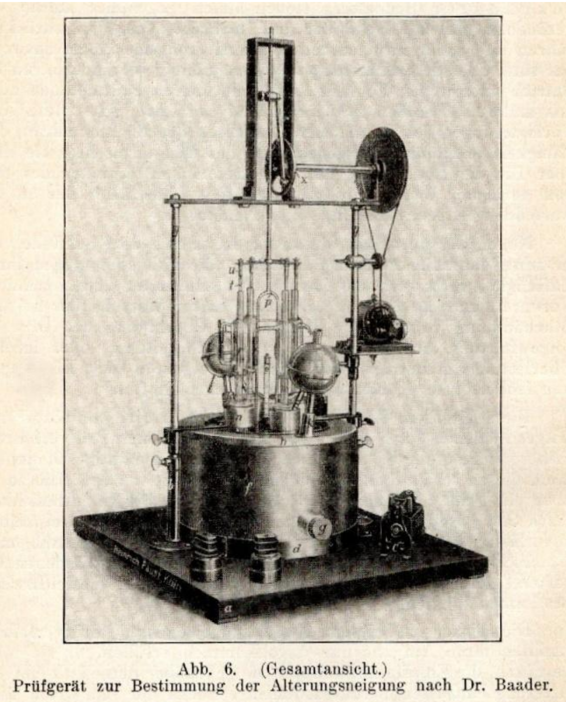

Figure 1: Dr. Baader's testing apparatus

3.2. TOST-Test (ASTM D943)

One of the first standardized tests was ASTM D943, also known as the Turbine Oil Stability Test (TOST), which was first published in 1947. In this test, the oil was exposed to oxygen, water and a metal catalyst at elevated temperatures (95°C) to simulate oxidative stress. This test measured the time it took for the oil to reach a certain level of acidity, indicating the onset of oxidation.

4. Advancements in Testing Methods

In response to the changing composition of turbine oils, further advances in oxidation testing techniques have been made in recent years. Modern turbine oils are formulated with highly refined base stocks that are low in aromatics and sulfur, which have an impact on their oxidation performance. New test methods have been proposed to more accurately simulate the oxidation processes in these modern oils. These methods include model bulk oil oxidation tests that consider a variety of temperature conditions, metal catalysts and antioxidant types.

4.1. Rotating Pressure Vessel Oxidation Test (RPVOT, ASTM D2272)

As turbine technology evolved, and operating conditions became more demanding, new test methods became necessary to better and more reliably evaluate the oxidative stability of oils. An important advance was the introduction of the Rotating Pressure Vessel Oxidation Test (RPVOT) in 1964. The test is standardized according to ASTM D2272. In this test, the oil, together with water and a copper catalyst, is placed in a pressure vessel that is pressurized with oxygen (6.2 bar) and rotated at a temperature of 150°C at a speed of 100 rpm. The time to achieve the significant oxygen pressure drop, indicates the oxidation stability of the oil (minutes RPVOT).

4.2. Turbine Oil Oxidation Stability Test (TOST) for Sludging and Corrosion Tendencies (ASTM D4310)

The Modified TOST is used to evaluate the sludge and corrosion tendency of oils by measuring the formation of sludge and corrosion on copper catalytic converters. This test method was published in 1983. It is a modification of the original TOST test and is completed after 1000 hours. At the end of the test, the amount of sludge formation and the degree of corrosion on the copper catalyst are evaluated.

4.3. Dry TOST (ASTM D7873)

The Dry Turbine Oil Stability Test was developed by Mitsubishi Heavy Industries (MHI) in 2004 in response to increased deposits on bearings. It was published in 2013 as ASTM standard D7873. This test method is used to evaluate the oxidation stability of inhibited turbine oils at 120 °C without water inclusion. It is a modification of the conventional TOST method (ASTM D943) in which water is excluded to simulate dry conditions.
The method evaluates the sludging tendency of steam and gas turbine lubricants during the oxidation process with the passage of gaseous oxygen and metal catalysts (copper and iron) at an elevated temperature of 120°C.

4.4. Lubricant Temperature Aging Test (LTAT, DIN51545)

This method is derived from an in-house method used by MAN Energy Solutions. Since the 1990s, this test has been used by the turbine manufacturer to qualify turbine oils. It consists of static ageing of turbine oils at a temperature of up to 180°C. A modified version of this method with a maximum temperature of 150°C was published in 2024 as DIN 51545. The standard method is a qualitative assessment of the temperature stability of a lubricant, i.e. it provides information on the tendency to form deposits and oil sludge under thermal load. The formation of oil-insoluble precipitation products during thermal aging is evaluated visually. As an option, the solids that are insoluble in n-heptane and the loss of mass can also be determined gravimetrically and used for a qualitative evaluation.

4.5. Turbine Oil Performance Prediction-Test (TOPP, ASTM work item under ballot)

In order to evaluate the performance of turbine oils, both the oxidation performance and the tendency to form varnish must be measured. This is attempted using an ASTM test method: The Dry TOST method described earlier. However, the test method's reporting system uses metrics that are not commonly used in condition monitoring. Therefore, the results may not be comparable to the actual performance of the turbine oil. Standardized test methods such as the MPC, RULER and RPVOT tests to report the results, the findings can be correlated to actual field performance. The test is referred to as the Turbine Oil Performance Prediction (TOPP) test, which was developed by Fluitec starting 2012 (figure 2). This standard method is currently under final review by the ASTM committee.

The test procedure consists of:

- Placing four (4) 350ml samples of new turbine oil are placed in glass test cells containing a steel/copper coiled wire catalyst conforming to ASTM D5846 specification.
- The test cells containing the turbine oil and catalyst coil are placed into a 120 °C (248ºF) temperature bath.
- The samples are allowed to equilibrate to 120°C (248ºF) for 20min. After equilibration, dry atmospheric air is bubbled through the test oil at a rate of 3L/hr to accelerate aging throughout the duration of the test.
- One sample cell is removed at three (3), six (6), nine (9), and twelve (12) week intervals for testing.
- On each sample, perform Viscosity, Acid Number, RPVOT, MPC & RULER. Supplemental tests include Foam and Demulsibility.

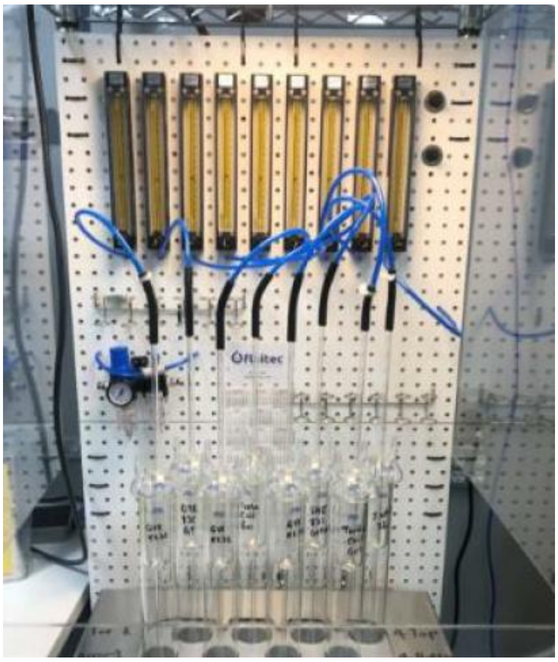

Figure 2: The Turbine Oil Performance Prediction (TOPP) test apparatus

TOPP Test Data Interpretation

The three most important parameters to measure in the TOPP test are the fluid’s oxidative stability at the end of the test, the MPC trend throughout the test and the observable deposits on the glassware. It is rare for viscosity, acid number, foam or demulsibility to change significantly.

In order to assess the oxidative stability at the end of test, an average of the percentage of amine antioxidants and the percentage of RPVOT value compared to new oil is obtained. In some formulations there is a direct comparison between RPVOT and amine antioxidants, however not in all formulations, so using an average of the two values provides a rounder picture. The highest performing oils may have 75% or more oxidation stability at the end of the test while older formulations may have <25%.

The maximum MPC value throughout the test period is used as a gauge of the fluid's potential varnish production. Oils with MPC values in the critical range (>30dE) are considered to have higher varnish potential. Some of the highest performing oils on the market will still have single digit MPC values at the end of the test.

Perhaps the most valuable part of the test is assessing the condition of the glassware at Week 12. The visual deposits represent actual deposits that would be expected to form in the field. The test tubes can be visually compared as can be seen in Figure 3. One can observe significant differences in deposit control performance by comparing the top row versus bottom row of test tubes.

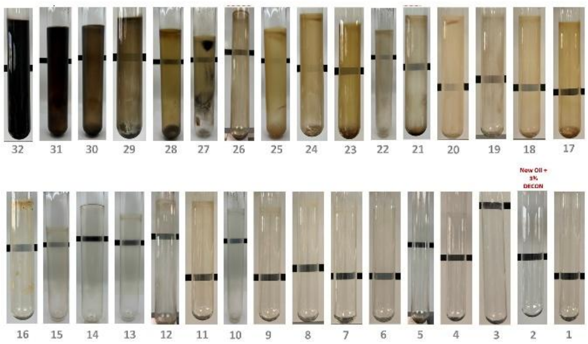

Figure 3: Glassware from 32 commercially available turbine oils at the end of 12 weeks in the TOPP test

In order to quantify the condition of the 12-week glassware, the total color is determined in the head space and fluid space and compared with the total color of both spaces in an unused test tube. This can be seen in Figure 4. It is interesting to also compare the head space of the 12-week glassware as some formulations develop crystalline deposits in this area.

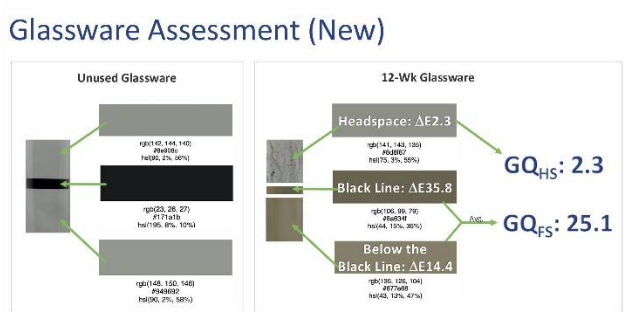

Figure 4: Determination of the Glass Quality Head Space and Glass Quality Fluid Space.

5. Oxidation Tests in Standards

The most important oxidation test in the first generation of turbine oil standards is the TOST test. It was implemented in the early editions of ISO 8068, ASTM D4304 and DIN 51515-1.

The second generation of standards is characterized by the introduction of the RPVOT test with a requirement of 750 minutes. This requirement was first implemented in company specifications. It was then adopted by national and international standards. Lubricants meeting these standards had to be able to withstand higher temperatures and have higher thermal stability.

In the meantime, a third generation of turbine oils has been developed. These oils have passed the tests against varnish described above. But these tests have not yet been included in national and international requirements.

6. Performance of turbine oils for Modern Gas Turbines

Performance is influenced by two factors that are equally important - the right selection of the product and the right approach to ensuring a long service-life.

6.1. Selection of the best suitable turbine oil

To select the most suitable products from the wide range of approved turbine oils, all types of stresses that occur in a modern gas turbine set today must be considered.

- *Thermal stress* occurs primarily in bearings, especially thrust bearings, which are the most stressed areas in the oil system. This is due to the pressure load, the temperature and the relative speed of the tribological interfaces.
- *Oxidative stress* occurs mainly where there is air in the oil, especially in the return lines and the tank. The oil degasses in the tank and the oxidative stress decreases again.
- *Varnish build-up*: A relatively new requirement arises from the occurrence of varnish in modern oil formulations, which is mainly due to the low solvency of the base oil. As a result, there is a need to differentiate between varnish-forming oils and varnish-resistant oils.

If all the requirements relating to thermal and oxidative stress and the tendency to form varnish are brought together, the TOPP test comes closest to the requirements in modern gas turbines. It can be assumed that the chemical reaction mechanisms are similar to those in the turbine because the test works at 120°C, which is close to the maximum operating temperature in bearings. In addition, air flow and catalyst metals are used in the test, which is also close to machine conditions. And the duration of the test, at 12 weeks, is still within acceptable limits if you are carrying out a development program or an approval process. This is generally only required for a new product or product modification in order to validate the properties.

Benchmarking

Each oil is ranked based on *Varnish Deposition* (glassware visual rating scale), *Varnish Production* (MPC), *Estimated Life* (Average of RULER & RPVOT). The importance of each attribute may then be assigned a weight. Typically, the weights shown in Table 1 are used.

Table 1: Weight of TOPP test values in order to benchmark different formulations.

Parameter	Weight
Varnish Deposition	3
Varnish Production	2
Estimated Life	1

Compiling this data allows one to benchmark different formulations, as can be seen in Figure 5.

Correlation to Field Results

One of the benefits of the TOPP test is that there is a direct correlation between an oil's performance in the test and how the oil performs in the field. This has been verified by comparing TOPP results with hundreds of in-service oil results.

Varnish Deposition	Varnish Production	Estimated Life	Overall Rank
15	21	2	17
28	32	28	30
25	27	19	27
16	25	4	19
10	11	11	10
8	10	24	11
2	3	14	3
21	15	23	20
4	16	5	6
14	13	10	14
19	24	27	25
23	23	16	23
22	20	21	22
2	1	15	1
1	9	12	4
7	7	3	5
17	14	7	16
24	18	30	26
27	22	6	23
26	31	31	29
12	8	22	13
29	26	25	28
13	19	13	18
30	29	29	31
11	17	18	15
31	30	32	32
9	2	20	7
6	12	17	9
5	6	26	8
18	28	9	21
20	5	1	12
3	4	8	2

Figure 5: Example of turbine oil benchmarking. Note, it is common to see oils with a long estimated life produce a lot of deposits

6.2. Ensuring long-term stability

First, the performance of a turbine oil is reflected in the trouble-free operation of the system without oil-related failures or deviations, such as bearing temperature fluctuations. Second, long life is also a criterion of an oil's performance, considering the time, labor, and financial resources that must be expended when an oil needs to be changed. And thirdly, the growing importance of sustainability in operating supplies is another factor that should not be underestimated.

All this leads to the conclusion that adding additives to the operating oil to extend its life is a good way to use the selected oil for a longer period of time and save resources. Of course, this procedure must also be verified analytically, e.g. by testing the compatibility of the mixture according to ASTM D7155.

And the additive solution must also be qualified by a TOPP test. For the product "Decon AO" this procedure was carried out with positive results.

Last but not least, in this way every filling can become a fill for life, if it is treated in the right way.

7. Conclusion

In conclusion, the development and specification of high thermal stress turbine oils for modern gas turbines have evolved significantly over the years. The increasing demands on turbine oils, due to higher power and efficiency of the turbines, have necessitated the development of advanced oxidation tests to ensure the long-term stability and performance of these lubricants. Historical tests such as the Baader oxidation test and the TOST test laid the foundation for assessing oxidation stability, while modern tests such as the RPVOT and the Dry TOST test have further refined the assessment process. The introduction of the third generation of turbine oils, tested against varnish formation, highlights the need to incorporate modern requirements into standards like the TOPP test. The selection of suitable turbine oil is crucial to withstand thermal and oxidative stress and to prevent varnish formation. Benchmarking for turbine lube oils can easily be done using TOPP test results. Ensuring the long-term stability of turbine oils through the use of approved additive concentrates can extend their service life, thus contributing to the sustainability and reliability of gas turbine operations.