Selecting a New Formulation of Industrial Gear Oil — Focus on EP Performance©

To replace an expensive and partially obsolete component-blend formulation of an industrial Extreme Pressure gear oil, several additive-package formulations were tested and compared with other oil companies' products. The paper covers the methodology used and the main results - with particular focus on the innovative 30-hour extended FZG test that is run under conditions of constant temperature. The results confirmed the suitability of the test method and its advantages over the standard FZG method. Based on this work, some of the formulations were selected as being suitable – provided that other in-house and external tests proved to give positive results as well.

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INTRODUCTION

Having decided to replace a very successful but expensive and partially obsolete component-blend formulation of industrial Extreme Pressure (EP) gear oil, various methods were used to ensure that the selected replacement would have superior protection of gear surfaces in both steel-on-steel and steel-on-bronze contacts.

Based on the local market demands, it was considered important that the new gear oil would give robust performance, while new requirements, like Flender approval or superior high temperature oxidation cleanliness, were not considered essential.

Initially, an SRV test machine was used in parallel with an FZG machine for steel-on-steel tests. However, the former was abandoned because the results obtained were not conclusive. The FZG tests were conducted at a well-equipped University laboratory.

The original intention was to complete the task quickly by proving the suitability of an additive package coded A.1, a front-runner at that time. Indeed, this formulation gave the best result in the standard 12-stage FZG test (DIN 51354 A/8,33/90). However, in the 30-hour test, it showed lack of robustness and was consequently rejected.

The project was concluded by giving special attention to an application where enhanced rust and corrosion protection was required, while maintaining good filterability and water separability. That work was described in presentations given in Pretoria and Esslingen *(1)*.

TEST EQUIPMENT AND METHODS

Description of the FZG Apparatus and Standard Test Method

The FZG test rig is one of a class of lubricant test machines that uses actual gears as test specimens and therefore simulates the sliding/rolling conditions found in gear contact. Other examples of this type of test ma-

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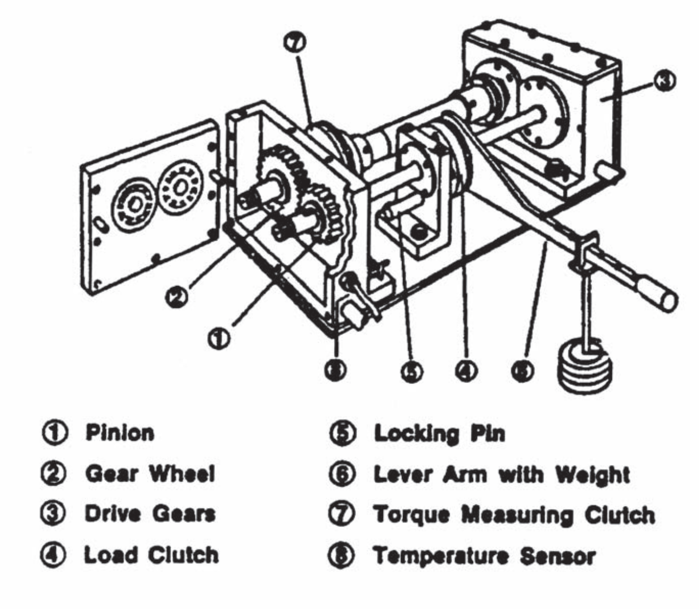

Fig. 1–The FZG apparatus during loading and with the front part opened (to access the gears).

chine are Ryder, IAE, and SAE tests. The latter uses two rollers instead of a gear set to achieve sliding and rolling movement.

A large selection of other test machines exists, where very simple specimens are used and where only one of the two contacts moves relative to the other. They normally run under full sliding motion. Movement can be unidirectional (Falex, 4-ball, Timken, Almen-Weiland, Alpha, pin-on-disc) or bi-directional, i.e. oscillating (SRV, Cameron-Plint). The contact configuration of these test techniques differ widely from those experienced in practice and the operating conditions (relative speed, loading etc.) on the contacts are also substantially different from those found in practical contacts *(2)*.

The reasons for the use of lubricant testers and for the inclusion of results obtained on such machines in product specifications for various lubricants are obvious: the behaviour of lubricants as friction and wear reducers, and how they are affected by their environment, i.e. pressure, movement, temperature and materials, is not fully understood and difficult to measure in practice. To simulate actual conditions on laboratory test rigs, under closely monitored (and controlled) conditions, and measure performance of different products on a comparative basis, is therefore an acceptable approach in itself. However, the tendency to extrapolate these results to practical conditions cannot always be substantiated. It is often the interpretation of test results and not the test itself that is taken out of context *(3)*.

There is very little doubt that the FZG machine is currently one of the most reliable and generally accepted tools for determining the load and wear performance of a large variety of gear lubricants *(4)*.

The FZG machine and the associated test procedures are described in the following international standards:

1. DIN 51354–1970: Mechanical testing of gear lubricating oils (gravimetric method)
2. DIN 51354–1990: Mechanical testing of gear lubricating oils (visual method)
3. ASTM D 5182–97: Evaluating the scuffing load capacity of oils (FZG visual method)
4. IP 334/86: Load-carrying capacity tests for oils (FZG Gear Machine)
5. CEC L-07-A-85
6. ISO WD 14635-1

The standard FZG test (A/8,33/90), also known as the 12-stage load test, was developed to determine the scuffing load capacity of gear oils *(5)* and is performed using type 'A' gears at a circumferential speed of 8.33 m/s with an initial sump temperature of 90°C. It is a dip-lubricated test and is normally performed on oils. The tooth profiles of the type 'A' pinion and gear are such that they ensure onset of scuffing much earlier than would be the case with gears designed for practical operation. A diagram of the test apparatus is shown in Fig. 1.

According to DIN 51354-1970, the sump of the test chamber of the FZG apparatus is filled with 1.25 litres of the test oil and the test gear set is loaded in stages and run for approximately 15 minutes (21,000 revolutions) at each load stage. At the end of each load stage, the sump oil temperature is recorded. It should be noted that no heat is removed (or added) by means of heating (or cooling) during the test, so that the final temperature at the end of each test gives an indication of the frictional energy converted to heat. After each load stage, the gears are removed, left to cool, cleaned, weighed and visually inspected according to the procedure set out in the test method. The following information is recorded for each load stage:

1. Mass of pinion and gear before and after the load stage,
2. Temperature of the oil in the sump at the end of the load stage,
3. Any visual changes, i.e. scratches, polishing of surfaces, scoring, scuffing or pitting marks.

According to the gravimetric method, failure of a lubricating oil can be defined as the onset of scoring as a result of breakthrough of the lubricating film, resulting in dramatic wear due to metal-to-metal contact. The standard FZG test (DIN 51354) defines the failure load stage as the load stage for which the mass loss exceeds the average mass loss over the preceding load stages by more than 10 mg.

The load stage of failure therefore becomes a norm related to the load-carrying capacity of the lubricant.

On completion of the test, the following parameters are reported:

1. Load stage of failure (or >12 if no failure occurred),
2. Specific mass loss, in mg/kWh,
3. Total mass loss during the test, in mg.

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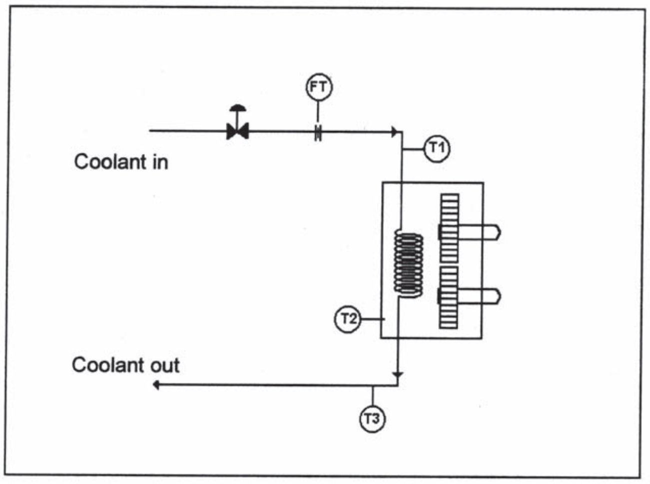

Fig. 2–FZG system with external cooling system.

Specific mass loss is the slope of the graph of mass loss versus energy transferred. In the case of gear oils, the specific mass loss is calculated over the load stages **before** the onset of scuffing (film breakthrough), i.e. it gives a comparative indication of scuffing load performance during normal operation.

Modifications to the Standard FZG Procedure

Rather than perform the test at loads higher than load stage 12, an extended wear test can be performed at a specific load stage (e.g. load stage 7 or 10) for a period of 30 to 150 hours and the mass loss over this period is then also reported. Michaelis *(6)* and *(7)* suggests that wear after an extended test period be reported as a specific mass loss and that this number be compared with the specific mass loss observed during the 12-stage load test. The latter gives an indication of the scuffing load capacity of the lubricant, while the former gives an indication of the wear resistance of the lubricant.

The maximum temperatures attained during the conventional FZG test are usually considerably higher than the temperatures normally experienced in practical gears. It is also important to recognise that different lubricants would attain different final sump temperatures at the end of each load stage due to different frictional behaviour of each lubricant under the same test conditions. The temperature profile therefore gives a qualitative indication of frictional heat generated during the test. Based on this information, it may be argued that the standard FZG test conducted in this manner does not conform adequately to practical operating conditions.

A further modification to the extended FZG test procedure would be to run the test at a chosen temperature and maintain this temperature for the duration of the test. In such a case, an external source of heat removal is necessary. This can be achieved by a cooling coil through which a coolant is passed, the flow rate of which can be manipulated to ensure a constant sump temperature. This configuration is shown in Fig. 2.

For performance evaluation of the gear oil candidates included in this paper, it was argued that this modified procedure would be adequate for purposes of comparing products under conditions as close as possible to the normal operating conditions. In other words, it makes correlations with actual operating conditions easier.

The test is now performed under exactly the same operating conditions as for the standard FZG test, but the sump temperature is maintained at a constant maximum value. In the case of the last batch of samples, the sump temperature was maintained as close as possible to 110°C.

Measurement of the flow rate, the inlet and outlet temperatures of the cooling medium, as well as the temperature of the lubricant in the test bed, give a direct and quantitative indication of friction dissipated as heat during the test. This information can, in addition to the load and wear characteristics, lead to an additional measure of comparison between competing products.

SAMPLES AND TEST RESULTS

The FZG results are summarized in Table 1. The original numbering of samples has been retained but the formulations have been coded. There were three suppliers of additive packages, coded A, B and C. After each test the involved suppliers were informed about their own candidates' results. Two additive suppliers submitted more than one candidate; for example, A.3 was a friction-modified version of the supplier A's previous candidate.

Samples 1 to 4 were in the first batch tested. The sample No. 1 (formulation X) was the original, proprietary, very successful but expensive component blend. This means that it contained a number of individual additives (some in very small quantities) from various additive suppliers.

The formulation B.2 was effectively tested three times because two of the samples were industrial gear oils purchased from two different competitive oil companies and identified by the laboratory staff as containing the same additive package. All the formulations contained sulphur and phosphorus but with varying degrees of activity.

Other than the elemental content (which is easy to determine in the lab), most additive suppliers do not disclose details of their chemistries and the selection is based on the performance requirements. All the candidates were to be suitable for premium-quality industrial gear oils. The candidate No. 3 was in fact not a premium product but, in the opinion of the additive supplier, it had strong, active chemistry thus could do well the test. It did not.

In addition to the additive package (EP, anti-oxidant, etc.), which was used at a recommended concentration, the blends also contained a Pour Point Depressant – the same amount of the same additive as used in the formulation X. All samples had a viscosity of ISO VG 320.

With regard to the base oils, one of the competitive companies was using the same solvent-refined Group I paraffinic base oils as were used in the candidates blended for the test. The other competitive oil company used different, but

Table 1—Test Result Summary

Sample		Standard FZG Test				30 Hours at Load Stage 10 Test						OK
#	Pack Code	Fail Stage	Total Mass Loss mg	Specific Mass Loss mg/kW.h	Note	Run Time h	Total Mass Loss mg	Temperature: Coolant, °C	Temperature: Sump, °C	Appearance, Wear Marks: Gear	Appearance, Wear Marks: Pinion	
1	X	>12	14	0.1064		30	19	25/29	110	Slight	Slight	Y
2	A.1	>12	3	0.0228	Best	30	101	25.5/30	138		Severe pitting	N
3	B.1	9	43 (Stage 12)	0.2575		3	Total failure	24/30.5	122	(2)	(3)	N
4	B.2	>12	6	0.0456		30	23	25/27.5	109			Y
5	B.2	11 (1)	44 (Stage 12)	0.3182		30	261	17.3/18.7	110	Slight	Slight	Y
6	B.2	12	57	0.4256		30	281	18.7/20.1	120		Slight	Y
7	C.1	>12	13	0.0684		30	126		110	(4)	(4)	Y
8	B.3	11	319	0.2088	Scuff on pinion	30	122		110	Blue marks	(5)	N
9	A.2	>12	26	0.1747	161°C	30	113		120	Scoring		N
10	A.3	>12	24	0.1823		30	188		102			Y

(1) Accepted as meeting the requirement (see the test).
(2) All teeth black on both sides. Impossible to identify which side was used in the standard test and which in the 30-hour test. Possibly because, in the standard test, all 12 stages were completed (the final temperature was 150°C = the second highest) although the failure occurred in the stage 9. Some plastic flow of metal towards the sides and the tips - creating grooves on some tips (usually with very shiny addendum). Some flaking. Rainbow effect less pronounced than on the pinion.
(3) Scoring, flaking, extensive shiny spots, only a few faces still showing honing marks but covered with "varnish." Strong plastic flow of metal towards the sides. Rainbow effect on sides: black near the tips, then red-orange-green-blue-purple towards the center of the pinion.
(4) Gears from the test No. 7 were unique in that they were uniformly very light brown suggesting prolonged mild overheating. This was judged to be both good and bad. Good because the oil provided an excellent protection to the gears that still retained the honing marks even after the 30-hour test. Bad because too much heat was generated which was considered to be one of the factors in the test. On the balance, the candidate C.1 was acceptable.
(5) The whole pinion light brown, slightly darker at tips. Some black faces or black spots. Otherwise honing marks visible under bronze-coloured "varnish."

also good quality, Group I base oils; in the results, it made no difference. Both brands of base oils were produced locally in Durban.

The second batch of samples comprised of samples 5 and 6, and the third one of samples 7 to 10. This is important to know because the batches, tested far apart from each other, were obviously exposed to different test severity. Thus the second batch was perhaps the most severe and the first batch the least severe. The severity of the third batch is now standard - due to an improved temperature control in the 30-hour extended FZG test (described above). Despite these differences, the results allowed us to select the best candidates with a degree of confidence.

Most of the samples passed the standard FZG test, showing no apparent wear marks after this test. The sample No. 5, despite its nominal failure, was tested over full 12 stages, which confirmed that the problem could be attributed to the definition of failure in the test method (a mass loss higher by 10 mg than the average loss in the previous load stages). This argument made the candidate acceptable in view of the acceptable total mass loss, and the most satisfactory appearance of the gears after 12 stages.

The samples 3 and 8 failed. The sample No. 8 was recommended to us as having superior thermal and oxidative stability - which unfortunately meant less active Extreme Pressure chemistry; consequently, it did not reach stage 12 in the standard FZG test.

In each case, after the standard FZG test, the gears were turned and re-used in the 30-hour test.

Only three candidates, A.3, B.2, and C.1, were considered acceptable after the 30-hour test (see the last column in Table 1).

Perhaps the most revealing result of the program was the appearance of the gears after the 30-hour extended FZG test. The following examples have been chosen from the first batch of samples 1 to 4. The standard FZG shape "A" pinion has pointed teeth that suffer much more distress than the more "normal-looking" matching gear. However, in the case of all acceptable candidates, both the pinions and the gears looked almost like new even after the 30-hour test (Fig. 3).

As mentioned, an early disappointment was the candidate No. 2 (Fig. 4) which gave outstanding results in the standard FZG test but failed the 30-hour test.

The difference between good results and bad results was so striking that it was not considered necessary to conduct a detailed analysis of the failed gears. In the worst case, the candidate B.1, the damage was so severe (Fig. 5) that some torn-off pieces of metal deposited in root lands of the pinion. In other cases, the gears were discolored by heat with a rainbow effect from brown to blue to orange to the normal silvery appearance in the central body of both gears (Fig. 6).

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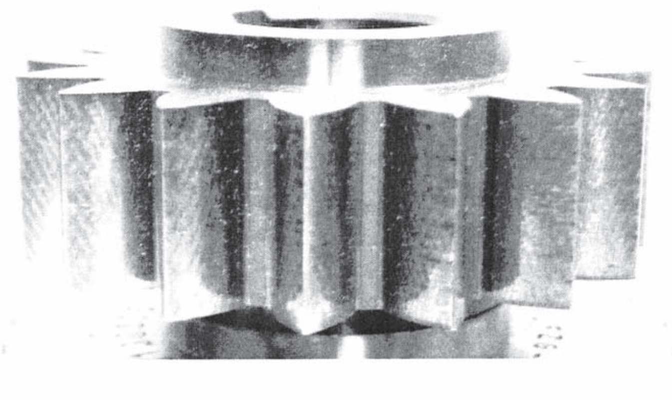

Fig. 3–Formulation B.2. Only the pinion is shown - placed on top of its matching gear. There is no apparent wear after the test No. 4 and the honing marks are still clearly visible on the tooth surfaces which were in contact during the standard FZG test (right hand side of the picture) and during the 30-hour extended FZG test (left hand side). The metal is not discoloured; both gears are still silvery in appearance. Note the pointed tips of the teeth.

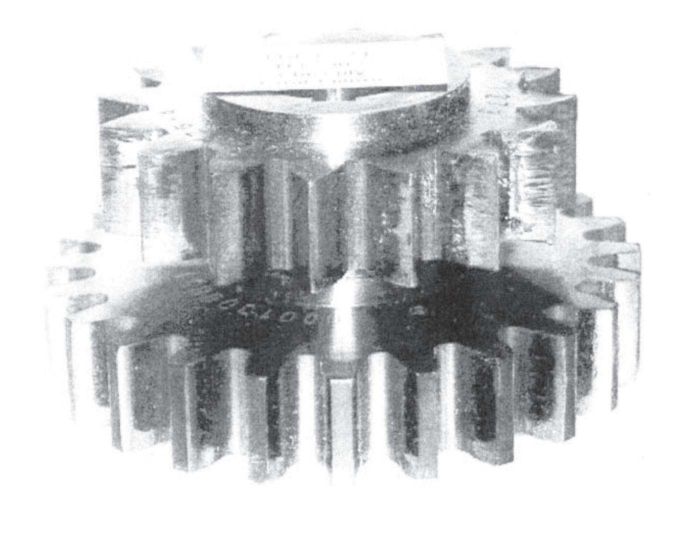

Fig. 5–After the test No. 3 (the pinion is placed on top of its matching gear).

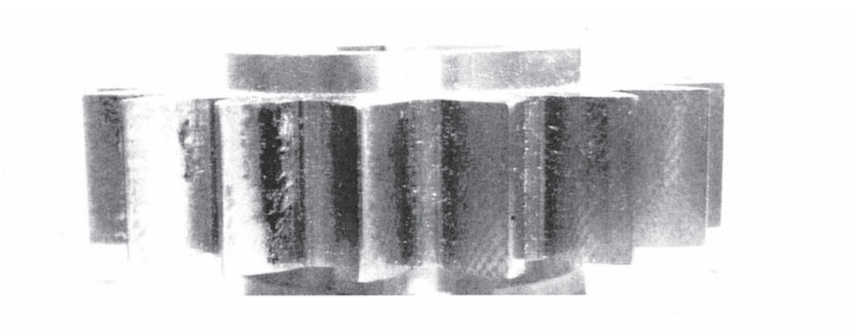

Fig. 4–The pinion after the test No. 2. There is no apparent wear and the hone marks are still clearly visible on the tooth surfaces that were in contact during the standard FZG test (right hand side of the picture). However, after the 30-hour test (left hand side) there was destructive pitting and spalling on most dedendum surfaces, some across the whole width, some confined to one half (possibly a slight misalignment but if so it did not affect the samples 1 and 4). The colour of the pinion was very light brown, slightly darker at tips, while the matching gear retained its silvery appearance and the wear marks were acceptable, with only a limited evidence of metal transfer to the gear.

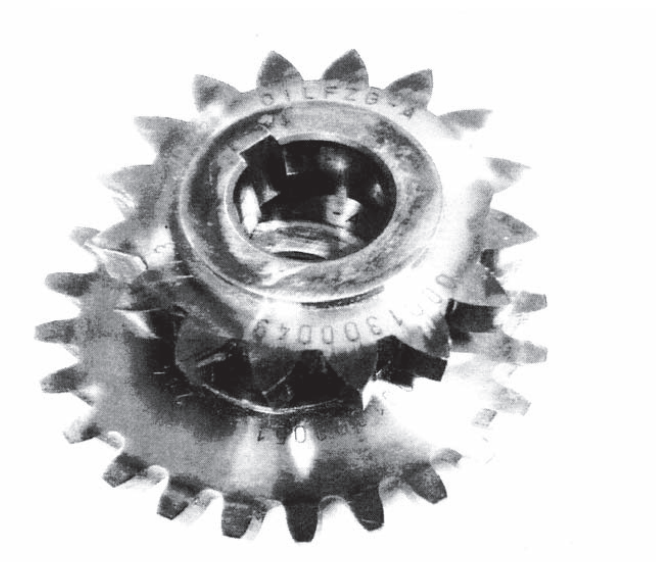

Fig. 6–Discoloured gears (the pinion is placed on top of its matching gear).

CONCLUSIONS

The results confirmed the suitability of the 30-hour extended FZG test method and its advantages over the standard FZG method. Based on this work, three formulations (A.3, B.2, and C.1) were selected as being acceptable and submitted to further in-house and external tests. One of them became the new approved formulation and proved to be a success as it replaced the previous complex formulation without any field problems.

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