SCORING TESTS OF AIRCRAFT TRANSMISSION LUBRICANTS AT HIGH SPEEDS AND HIGH TEMPERATURES

H. Winter and K. Michaelis*

Aircraft engines always contain gears that have to be lubricated under conditions of high speeds and extremely high temperatures. In this field of application scoring damage can be likely to occur. In Europe and partly also in the USA the scoring load capacity of gear oils is expressed in terms of FZG Scoring Load Stage. The FZG Gear Test Rig is described. The normal test procedure A/8.3/90 as standardized in DIN 51 354 using A-type gears at a pitch line velocity of v = 8.3 m/s and a starting oil temperature of 90°C is presented. A modified procedure at double speed and increased oil temperature A/16.6/140 is discussed. The scoring load capacity of aircraft transmission lubricants is worldwide expressed in Ryder Gear Test results. Because of the high costs and problems with the availability of test gears a modified FZG Ryder Test was developed. The method is presented and comparative results of typical aircraft engine oils in the FZG, the FZG-Ryder and the original Ryder Gear Test are shown. From this experience it becomes obvious that alternative test methods for the evaluation of scoring load capacity of aircraft transmission lubricants can be available in the near future.

1. Introduction

With increasing power transmission per volume, increasing speeds and increasing temperatures the demands on lubricants for application in aircraft gearing have increased accordingly. Besides physical properties like viscosity and chemical properties like oxidation stability the technological properties like scoring load capacity have to be tested under conditions close to practice. As scoring is affected by different properties of the lubricant - viscosity as well as chemical composition - gear test procedures were developed and compared with the behavior of the lubricant in practice. These test methods are the Ryder Gear Test in the USA, the IAE test in Great Britain, and the FZG test in Germany. In the following, test procedures on the FZG back-to-back gear test rig and results with aircraft lubricants are described.

2. Standard Test A/8.3/90

The test rig is of the back-to-back type with a mechanical power circuit. The test torque is applied by lever and weights at the load clutch and can easily be calibrated and controlled through the distortion of the torsional shaft (see Fig. 1). A specially designed gear profile, so-called A-type gears with high sliding and thus with high scoring risk are used. Fig. 2 shows the gear profile with the velocity and pressure distribution along the path of contact; table 1 gives the main gear data. Under conditions of dip lubrication at a starting oil temperature of 90°C the gears are run for 15 min. in one load stage (Fig. 3). The load is increased stepwise in 12 load stages until scoring occurs on the flanks. The oil bath is not cooled so that a maximum oil temperature in the twelfth load stage of approx. 140°C is reached. Scoring failure can be assessed either by visual control (Fig. 4) or by weighing the gears after each load stage and plotting the weight loss against transmitted work (Fig. 5). A steep increase in weight loss indicates scoring failure. The scoring load stage is reported and for the gravimetric method the specific wear rate gives an additional value on the relative wear behaviour of the lubricant.

This test method is standardized in Germany in DIN 51 354 /1/ and in Europe in CEC L-07-A-71 /2/. The results of the test express a relative rating of scoring load capacity of different oils. Calculation procedures were established in DIN 3990 and ISO 6336 /3, 4, 5/ for the calculation of the scoring risk of practical gears using the FZG scoring load stage as the "strength value" for the lubricant. Results for typical aircraft oils in the FZG standard test A/8.3/90 are shown in Fig. 6. The relative rating is comparable with results of the Ryder Gear test with these oils.

3. Special Test A/16.6/140

As high performance EP gear oils usually passed the 12 load stages without failure a modified, more severe test procedure at an increased speed of v = 16.6 m/s and for high temperature application at starting oil temperature of 140°C was established /6/. Because the oil is not cooled during the test temperatures up to 180 - 200°C are reached in load stage 12 of this procedure. Again the results of aircraft lubricants are shown in Fig. 7. It is interesting to note the very high scoring load obtained with the Shell 0-160 oil compared with the standard test. The result was proved by duplicate testing.

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* Prof. Dr.-Ing. Hans Winter is head of the Institute of Machine Elements and the Laboratory of Gear Research (FZG), Technical University Munich, Arcisstrasse 21, D 8000 München 2, West Germany. Dipl.-Ing. Klaus Michaelis is chief engineer at the FZG.

According to Maier /7/ a very rapid decrease of the oil performance as related to scoring is observed. This is confirmed with tests on used oils vs new oil in the A/16.6/140 procedure as shown in Fig. 8. Significant reductions in scuffing performance can be seen with increasing use of the oil /7/.

4. FZG Ryder Test R/46.5/74

From different research projects /8, 9, 10, 11/ it is known, that the scoring behavior of different lubricant types with increasing velocity may be very different. In Fig. 9 the scoring load for different base oils and different additive systems is plotted against velocity. From this graph it is evident that a different ranking of the oils is possible when tests are performed at different pitch line velocities.

Because of the high costs of the Ryder test rig and test gears as well as problems with the availability of test gears, a research project was initiated and funded by the German Ministry of Defence. The aim was to develop a test rig and test procedure on a modified FZG test rig which gave equivalent results as compared to Ryder Gear Tests /12/ (Fig. 10).

The principle of the test rig can be taken from Fig. 11. Table 2 lists the differences in the rig design as compared with the original Ryder rig. Because of almost the same center distance of the two rigs FZG R-type gears (Fig. 12) could be designed very close to the original Ryder gears. A comparison of the main gear data is given in Table 3. Table 4 shows a comparison of the gear materials used.

Fig. 13 shows the test procedure. The oil to be tested is heated to the test temperature of 74°C. For every test an oil quantity of approx. 5 l is necessary. The oil is sprayed on the gears at a flow rate of approx. 0.5 l/min. Then the torque of load stage 1 is applied. The load in every load stage can be taken from table 5. The motor is started; the running time is 10 min per load stage. After every load stage the gears are inspected with a microscope and the scored area on each flank is recorded. For this purpose a grid is incorporated in the microscope such that each square represents 5% of the active flank area of a tooth. Thus the location and the size of the scoring marks can easily be recorded. The percentage of damage in each load stage is determined and plotted against the load in a logarithmic chart (Fig. 14). The test is terminated when more than 30% of the active flank is scored. Scoring load is interpolated as the normal tooth load when 22.5% of the flank shows scoring failure. The test on one oil is run with both flanks of the test gear. As result the mean value of all test runs as well as every single result is recorded.

In the course of the investigations a variety of different lubricants - straight mineral oils, mineral based EP oils and different synthetic lubricants - were tested in the FZG Ryder Test and compared to results obtained in the original Ryder machine. The results are plotted in Fig. 15. Fig. 16 shows comparative results for typical aircraft oils in the original Ryder /12/ and the FZG-Ryder test. A very good correlation is observed. In the next few months comparative testing of some commercial oils from different manufacturers and different specification will be done.

The first investigations were started with increased oil temperature to address the increased temperatures in turbines of the future. Tests with 0-160 were performed at 115°C instead of 74°C. The results are shown in Fig. 16. By a modification of the oil spray device even higher temperatures can be achieved when high temperature testing is necessary.

5. Conclusion

Different test methods on modified FZG back-to-back gear test rigs under high speed and high temperature conditions were discussed.

For the evaluation of typical aircraft lubricants a new test procedure FZG R/46.5/74 showed good correlation with test results in Ryder Gear Testing. The costs of the modified FZG test rig and test gears are approximately 25% of a Ryder Gear Test Rig and of original Ryder test gears.

Comparative testing of a wider range of commercial oils will be done in the next couple of months. To meet future requirements of aircraft lubricants in the high temperature range investigations at increased test temperature were started.

6. Acknowledgement

The authors would like to thank the German Ministry of Defence for the funding of the reported investigations and for the possibility to present the results in this publication.

7. References

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2 CEC L-07-A-71: Load Carrying Capacity Test For Transmission Lubricants.

3 DIN 3990: Grundlagen für die Tragfähigkeitsberechnung von Gerad- und Schrägstirnrädern.

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Table 1: Geometry of Test Gears Tooth Profile A

Center distance	a	91.5	mm
Number of teeth pinion	z_1	16	-
gear	z_2	24	-
Module	m	4.5	mm
Tooth width	b	20	mm
Pitch diameter pinion	d_{w1}	73.2	mm
gear	d_{w2}	109.8	mm
Addendum modification pinion	x_1	0.8635	-
gear	x_2	-0.5	-
Pressure angle	α	20	deg
	α_{wt}	22.5	deg
Length of recess path	e_1	14.7	mm
approach path	e_2	3.3	mm
Max. sliding velocity	v_{g1}	0.67v *	m/s

* pitch line velocity in m/s

	Original Ryder	FZG-Ryder	Units
load application	axial displacement	torque	
load measurement	recalculated from hydraulic pressure	distortion of calibrated shaft	
center distance	88.9	91.5	mm
pinion speed	10 000	9706	rpm
pitch line velocity	46.5	46.5	m/s
spray lubrication:			
oil flow rate	0.27	0.5	l/min
oil temperature	74	74	°C

Table 2: Comparison of Machines and Operating Conditions of Original Ryder and FZG Ryder Test

		Original Ryder	FZG-Ryder	Units
center distance	a	88.9	91.5	mm
number of teeth	z_1/z_2	28/28	30/30	-
module	m	3.175	3.0	mm
working pressure angle	α_{wt}	22.5	22.5	°
tooth width	b_1/b_2	6.35/26	6.25/26	mm/mm
tip relief gear	C_{a2}	0	15	µm
relative sliding speed	v_{gmax}/v	0.28	0.28	-
material:				
case carburized		AMS 6260	14NiCr14	-
surface hardness	HRC	60-62	60-62	-
surface roughness	CLA	0.3-0.5	0.3-0.5	µm

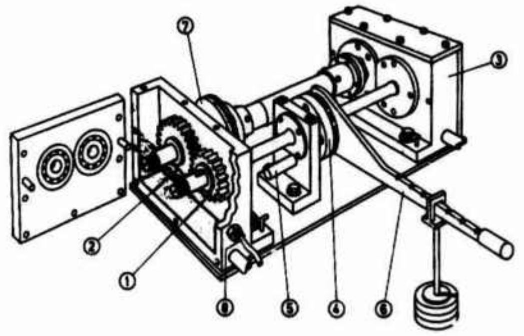
Table 3: Comparison of Original Ryder and FZG Ryder Gears

mean content of	AMS 6260	14 NiCr 14
C	0.11 %	0.15 %
Si	0.27 %	0.25 %
Mn	0.55 %	0.40 %
P_{max}	0.025 %	0.035 %
S_{max}	0.025 %	0.035 %
Cr	1.2 %	0.80 %
Mo	0.12 %	-
Ni	3.25 %	3.5 %

Table 4: Comparison of Gear Materials of Original Ryder and FZG Ryder Gears

Load Stage	Torque in Nm	Tooth Load in N/mm	in lb/in
1	17.5	66	375
2	35.0	131	750
3	52.5	197	1125
4	70.0	263	1500
5	87.5	329	1875
6	105.0	394	1250
7	122.5	460	2625
8	140.0	526	3000
9	157.5	591	3375
10	175.0	657	3750
11	192.5	723	4125
12	210.0	788	4500
13	227.5	854	4875
14	245.0	920	5250
15	262.5	985	5625
16	280.0	1051	6000

Table 5: Load Stages of the FZG Ryder Test



① PRÜFRITZEL
TEST PINION

② PRÜFRAD
TEST WHEEL

③ ÜBERTRAGUNGSGETRIEBE
DRIVE GEAR

④ BELASTUNGSKUPPLUNG
LOAD CLUTCH

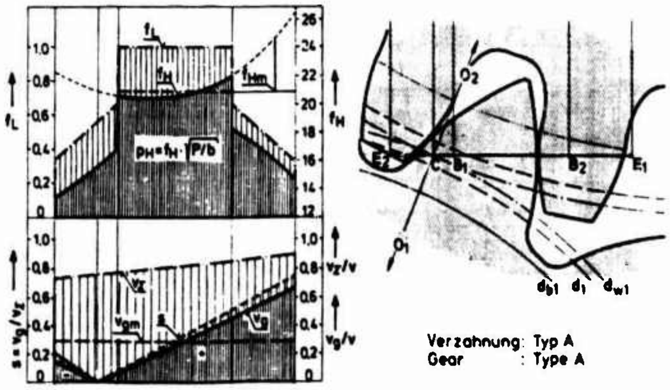
⑤ ARRETIERBOLZEN
LOCKING PIN

⑥ BELASTUNGSHEBEL MIT GEWICHTEN
LOAD LEVER AND WEIGHTS

⑦ TORSIONSMESSKUPPLUNG
TORQUE MEASURING CLUTCH

⑧ TEMPERATURFÜHLER
TEMPERATURE SENSOR

Fig. 1: FZG Gear Test Rig (Schematic View)



Verzahnung: Typ A
Gear : Type A

Fig. 2: Load and Speed Distribution (A Type Gears)

Fig. 3: FZG Scoring Test

GEAR TYPE A

DIP LUBRICATION WITH STARTING OIL TEMPERATURE AT BEGINNING OF EVERY LOAD STAGE ϑ_{OIL} = 90°C, WITHOUT COOLING

PITCH LINE VELOCITY v = 8.3 M/S

DRIVING PINION

LOAD STEPWISE INCREASED UNTIL SCORING OCCURS

FAILURE CRITERION:

VISUAL METHOD:	MORE THAN ONE TOOTH WIDTH SCORED AREA
GRAVIMETRIC METHOD:	MORE THAN 10 MG OVER THE AVERAGE WEAR RATE

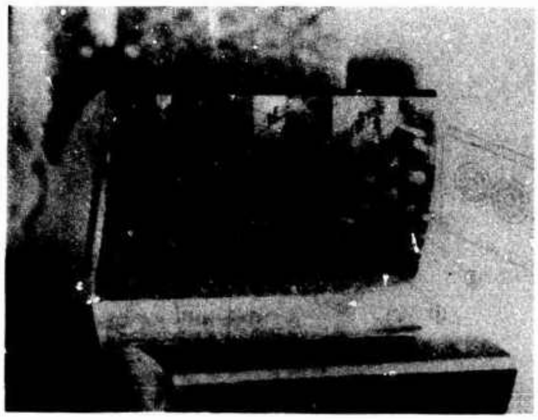
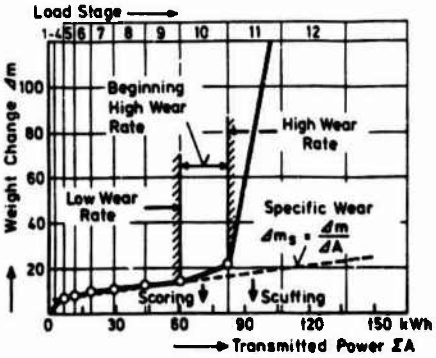


Fig. 4: Flank Appearance Scoring



Oil Code: Y

Result:
Failure Load Stage 11
acc. Jump in
High Wear Rate

Scoring Torque:
$T_{1T} = 450{,}1$ Nm

Specific Wear:
Load Stage 4 to 9

Δm_s below 0,27 mg/kWh
($\approx$ 0,15 mg/kWh)

Fig. 5: Result of an FZG Test (Gravimetric Method)

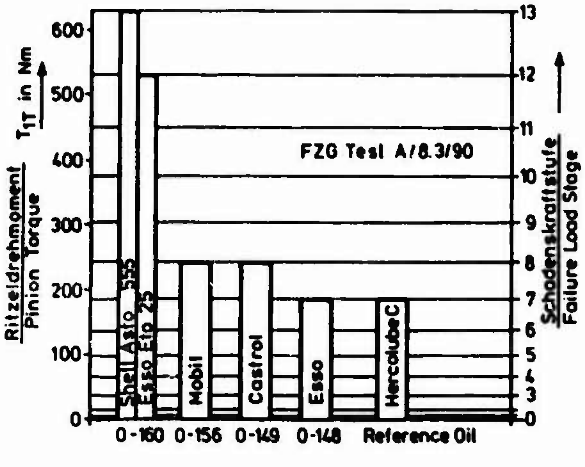


Fig. 6: Scoring Load Capacity of Aircraft Lubricants in the FZG Standard Test A/8.3/90

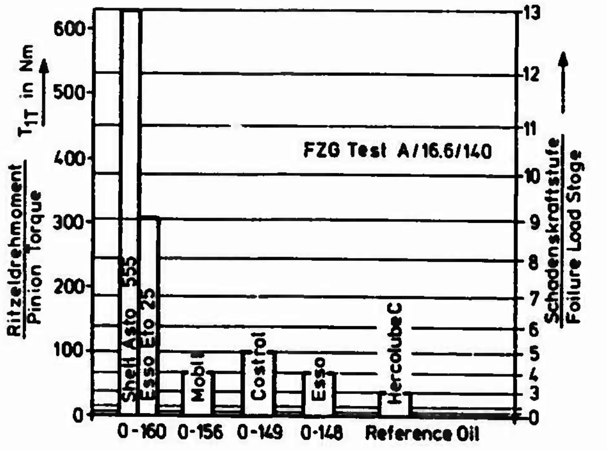


Fig. 7: Scoring Load Capacity of Aircraft Lubricanta in the FZG Special Teat A/16.6/140

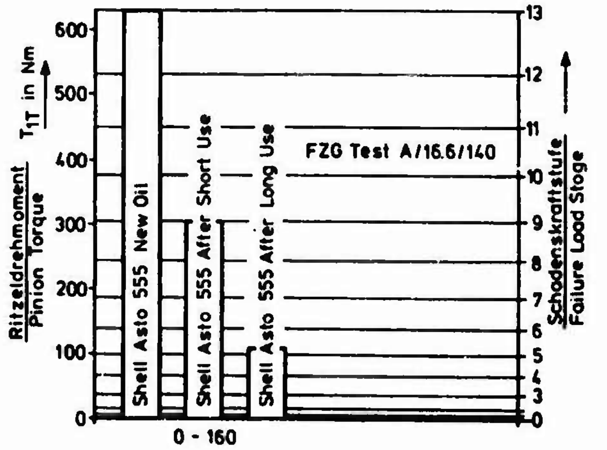


Fig. 8: Decrease of Scoring Load Capacit^ of Used Oil

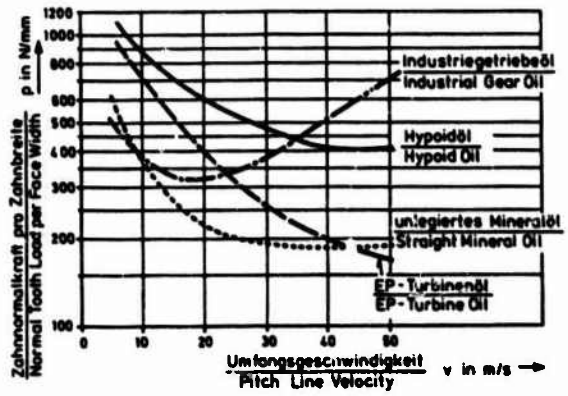


Fig. 9: Scoring Load for Different Gear Oils

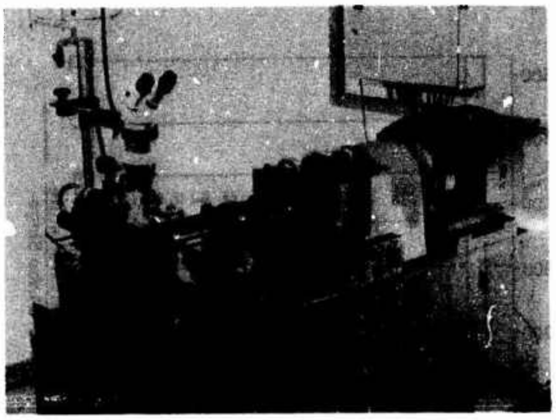


Fig. 10: Photo of the FZG Ryder Gear Test Rig

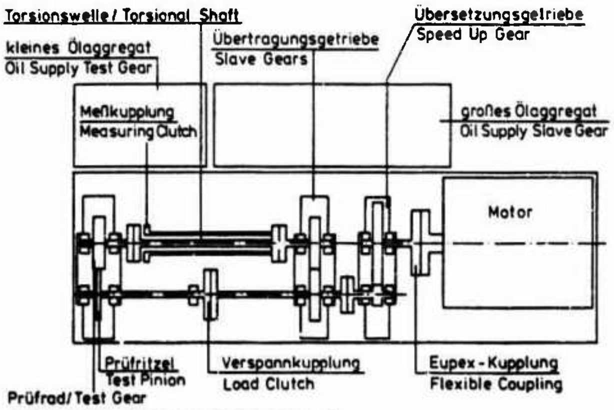


Fig. 11: FZG Ryder Gear Test Rig (Schematic View)

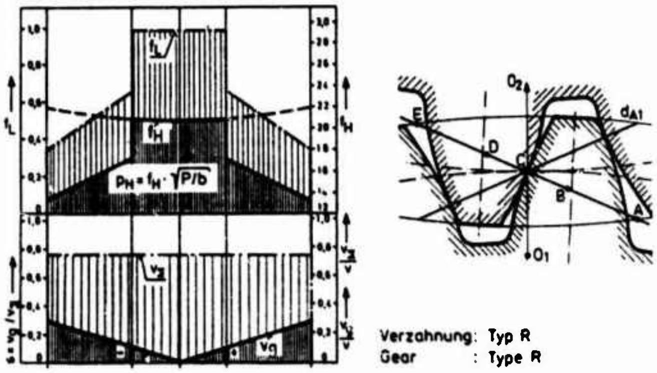


Fig. 12: Load and Speed Distribution (Gear Type R)

GEAR TYPE R

SPRAY LUBRICATION WITH CONSTANT OIL TEMPERATURE OF 74°C. OIL FLOW $\dot{V}$ = 0.5 L/MIN.

PITCH LINE VELOCITY v = 46.5 M/S
DURATION PER LOAD STEP T = 10 MIN

LOAD STEPWISE INCREASED UNTIL SCORED AREA ON THE PINION FLANK EXCEEDS APPR. 30% OF ACTIVE FLANK

FAILURE CRITERION:
MORE THAN 22.5% OF ACTIVE FLANK AREA SCORED.
SCORING LOAD DETERMINED BY LINEAR INTERPOLATION

Fig. 13: FZG Ryder Test

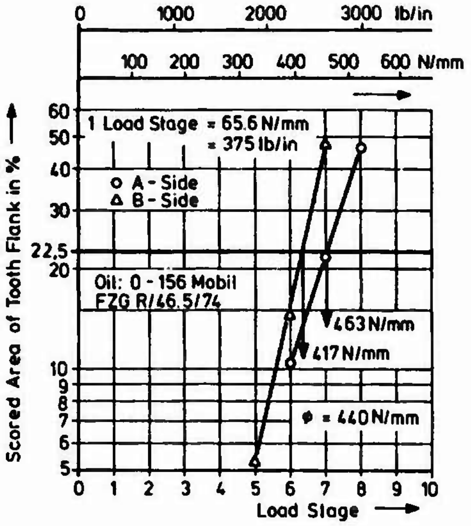


Fig. 14: Evaluation of Scoring Load in the FZG Ryder Test

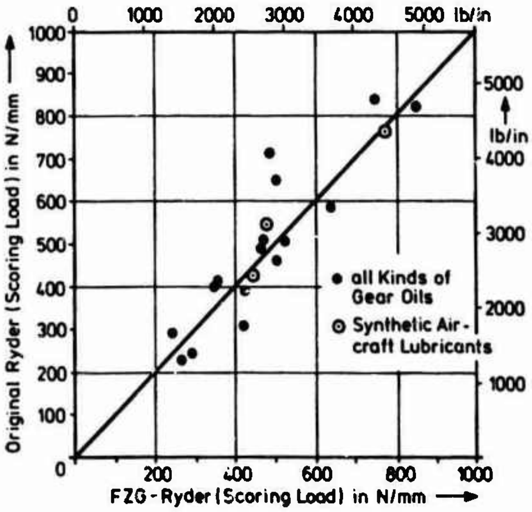


Fig. 15: Comparison of Scoring Load in the Original Ryder and the FZG Ryder Test

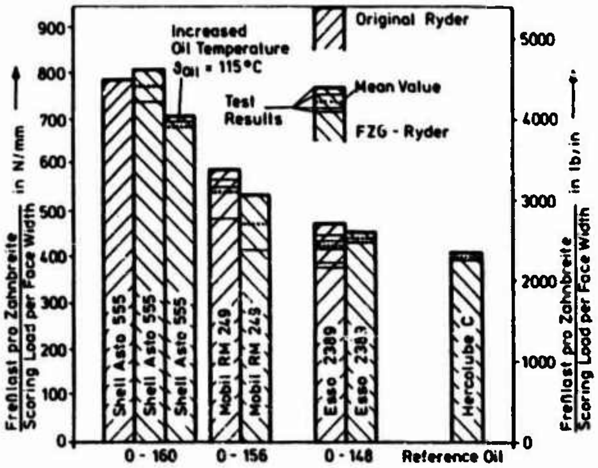


Fig. 16: Comparative Results of Ryder and FZG Ryder Tests for Aircraft Lubricants