Lubricity Evaluation of aviation fuels by a ball-on-disc technique

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Introduction

It is well known that liquid hydrocarbons such as diesel and aviation fuels need some measure of lubricating ability to protect moving parts in fuel systems. These systems normally operate in the boundary lubrication regime and the generation and properties of protective boundary lubrication layers have been widely investigated [1-4].

It is particularly difficult with aviation fuels to find a suitable laboratory test that will not only discriminate between fuels in terms of lubricity, but where results will also correlate with the known field performance of the fuels [5,6]. The one test method which at present seems to be most favoured for the assessment of the relative lubricity performance of aviation fules is the BOCLE [7] test. In this ball-on-cylinder lubricity evaluator test a ball in a vertically mounted chuck wears against an axially mounted steel cylinder under a load of 9,8 N for 30 minutes. The cylinder rotates partially immersed in the fuel under evaluation and transports the fuel to the ball/cylinder interface. The size of the wear scar generated on the ball is a measure of the fuel lubricity. During the evaluation the atmosphere in the test chamber is maintained at 25 °C and 10% relative humidity.

As the BOCLE equipment was not available for the lubricity evaluation of locally produced aviation fuel, the need arose for an assessment method which would yield comparable results to the BOCLE test. A ball-on-disc method was developed for this purpose.

Experimental

The wear test rig (shown in Fig. 1), used in this investigation consists of a 12,7 mm diameter ball on a counter balanced arm, loaded against a horizontally rotating steel disc. Load to the system is applied by means of dead weights on the load arm. The disc is driven by a variable speed motor through two reduction gearboxes resulting in a speed range of 0-115 r.p.m. The pivoting point of the load arm can be adjusted relative to the centre of the disc thus allowing selection of the wear track diameter on the disc. In this work a track diameter of 100 mm was used.

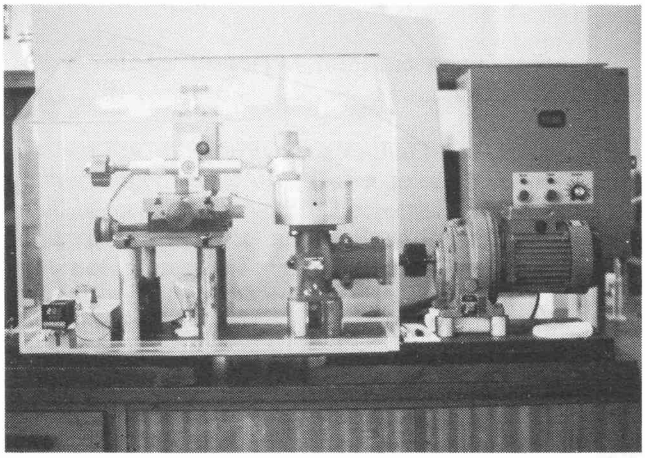

Figure 1 – Ball-on-disc wear test rig

A sample (~ 2 ml) of the fuel to be tested was applied to the disc surface and allowed to distribute evenly over the surface of the turning disc. The ball on the load arm was then gently lowered onto the running disc and timing started at the moment of contact between the ball and disc. In most of the tests a test time of 30 minutes was employed. At the end of the selected test time the ball on the load arm was lifted from the disc while it was still running. The wear scar diameters on the test balls were measured in two directions, parallel and perpendicular to the wear direction, using a microscope with a micrometer equipped stage. Wear scar diameters (WSD) were taken as the mean of the two measurements.

Initially the experiments were conducted under ambient laboratory conditions with air temperatures ranging from 19 to 24 °C and the relative humidity (RH) in the range 40-50%.

Under these conditions the results were found to be extremely irreproducible. It is known that in the BOCLE test both the temperature and humidity have to be accurately controlled to obtain reproducible results and the possibility existed that the same applied to the ball-on-disc (BOD) test.

A perspex box was constructed over the test rig, in which the air temperature can be controlled at temperatures above the laboratory air temperature. The RH is controlled by flushing the box with dry nitrogen gas until the required RH value is attained and then adjusting the nitrogen flow to maintain the selected RH value. Relative humidity values are determined with a Testoterm model 6100 Hygrotest instrument utilizing a capacitive thin film humidity sensor.

Further tests were mostly conducted under standard atmospheric conditions with the air temperature at 25 ± 1 °C and the RH at 13 ± 0,5%.

A set of 9 aviation fuels were used for evaluation and development of the test procedure. These fuels, not only varied in sulphur content, but were also derived from three different processes.

The steel balls used in the tests were grade 10-12,7 mm AISI 52100, HRc 62-64, steel balls obtained from RHP South Africa. These balls were ultrasonically cleaned, first in 60-80 °C petroleum ether followed by AR grade acetone. After cleaning care was taken not to touch the balls by naked hand before use.

A disc 12 mm thick and 120 mm in diameter was machined from AISI 52100 steel, heat treated to HRc 36 and then surface ground to obtain flat parallel surfaces. The wear surface of the disc was subsequently rubbed by hand

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*Tribology and Surface Engineering Programme, Division of Materials Science and Technology, CSIR on dry SiC paper of different grit sizes supported on a flat glass plate to give the required random surface finish. After each wear experiment the wear track on the disc surface was removed by rubbing the disc face on SiC paper. After each such restoration of the wear face on the disc, the surface finish was measured in 8 positions using a Hommel surface profilometer to obtain the mean surface roughness (Ra) value.

When the lubricity of low lubricity fluids such as aviation fuels is evaluated great care has to be exercised in the cleaning of the disc after each re-surfacing operation. Not only must all the SiC particles be removed from the surfaces but any contaminant which may improve the lubricity must be avoided. Good results were obtained when the disc was first wiped with paper tissue wetted with petroleum ether until no discoloration of the tissue surface could be detected. This was followed by 10 minutes ultrasonic cleaning in 60-80° petroleum ether, a rinse with petroleum ether from a wash bottle and finally a rinse with AR acetone. In further handling of the disc all contact with the cleaned wear surface was totally avoided.

Results and discussion

During the course of this investigation the influence of the surface roughness of the disc on the size of the wear scar was examined. Ball-on-disc wear tests were conducted at disc surface roughness values of 0,10-0,13 μm, 0,20-0,23 μm and 0,40-0,42 μm Ra. The results of these tests are shown in Table 1.

These WSD values show that at low speed (0,1 m/s) there is a decrease in WSD with increasing surface roughness. This decrease can possibly be attributed to more fluid being retained in the ball/disc conjunction at higher surface roughness values. This would tend to decrease the boundary lubrication character of the contact slightly and in this way the wear on the ball would also be slightly decreased. At the higher disc speed (0,5 m/s) there is no distinct trend in the change of WSD with surface roughness. It is assumed that at this speed the degree of boundary lubrication does not change with the different surface roughness values.

Reproducibility of results were found to be the best at a disc surface roughness of 0,2 μm Ra and as this was readily achieved by rubbing the disc on 180 grit SiC paper, most of the further work was done using the disc with this surface finish.

Table 1 Influence of disc surface roughness on wear scar diameter at 13% RH, a load of 14,7 N and a 30 minute test time

Wear Scar Diameters, mm						
Fuel No.	Speed 0,1 m/s Surface roughness, μm Ra			Speed 0,5 m/s Surface roughness, μm Ra		
	~0,1	~0,2	~0,4	~0,1	~0,2	~0,4
1	0,49	0,45	0,41	0,52	0,51	0,50
5	0,44	0,42	0,39	0,47	0,43	0,45
8	0,49	–	0,41	0,55	0,57	0,60

The relationship between test time and the size of the wear scar on the ball is graphically illustrated in Fig. 2 for fuels 1 and 5. The tests were done with a 0,2 μm Ra disc running at a speed of 0,5 m/s, the applied load 14,7 N and the RH 13%. The curves show that initially the WSD increase fairly rapidly but after a test time of 30 minutes the rate of increase diminishes. This resulted in the selection of 30 minutes as the standard test time.

The influence of RH on the WSD is demonstrated in Fig. 3. Wear tests with fuels 1, 5 and 8 were conducted using a disc with a surface roughness of ~0,2 μm Ra, a load of 14,7 N, speed 0,5 m/s and a run time of 30 minutes. The RH was varied, and controlled at selected levels between 2% and 30% by means of the nitrogen gas flow through the environmental control box over the test rig. These results clearly show that in determining the relative lubricity of these fuels by the ball-on-disc method, the WSD is extremely sensitive to changes in RH. Care should consequently be taken to ensure that the RH is kept as constant as possible when doing the tests.

Microscopic examination of the wear scars on the test balls shows the presence of a well adhered surface layer on the scar surface. The micrographs in Fig. 4 illustrate the appearance of the scars developed during the testing of fuel 5 at different RH levels. They do not only show the increase in scar size with increasing RH but also how the surface layer changes from a continuous layer covering the full scar area at low RH to a layer with a much more patchy appearance at high humidity. Auger electron spectroscopic analysis has shown that this surface layer is an iron oxide, indicating that the wear mechanism involved is oxidative.

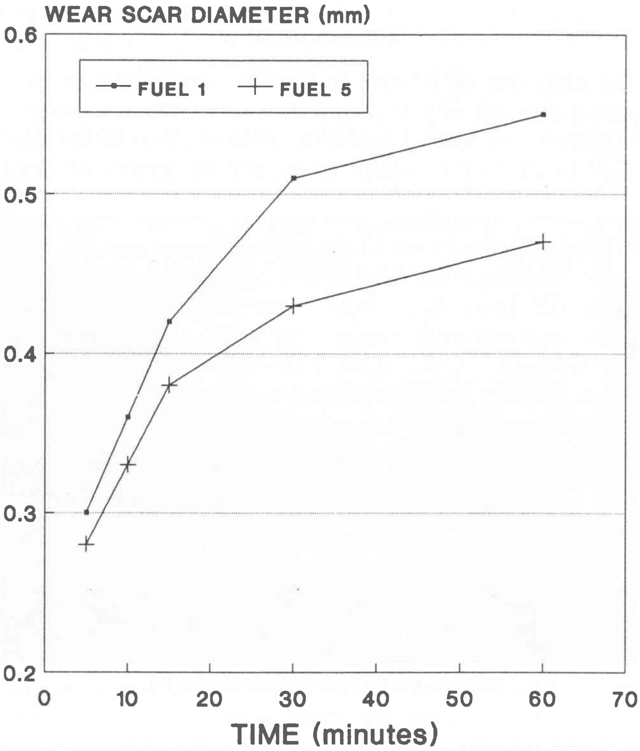


Figure 2 – Relationship between WSD and test time

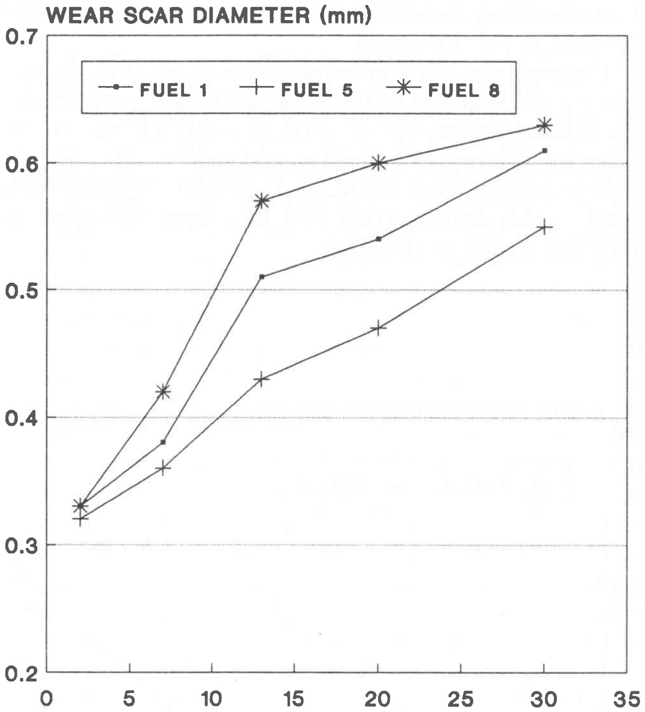
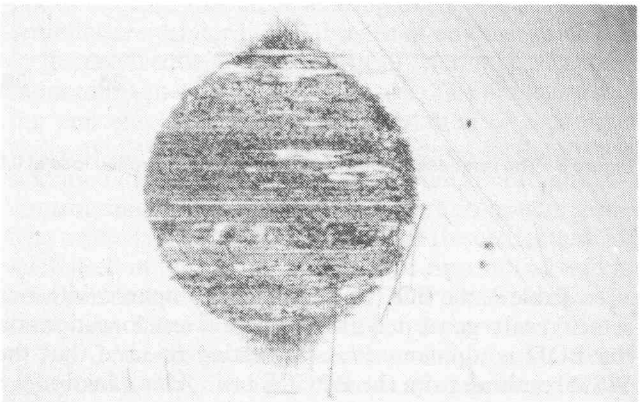


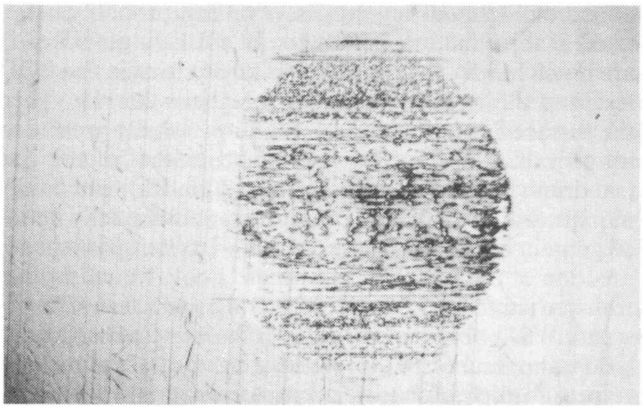
Figure 3 – The influence of relative humidity on WSD

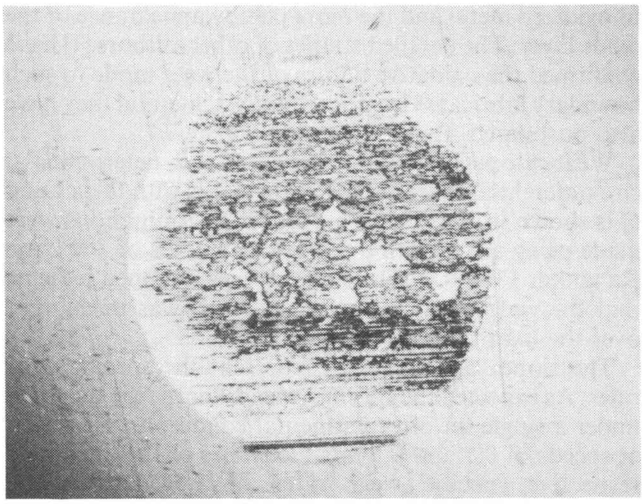
2% RH 7% RH

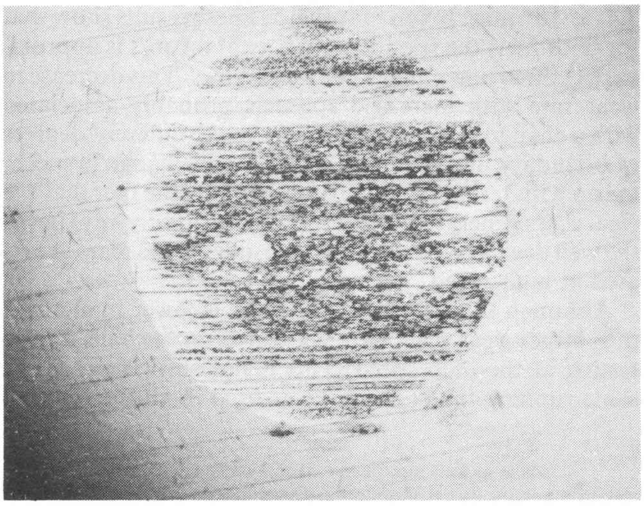
13% RH 20% RH

30% RH









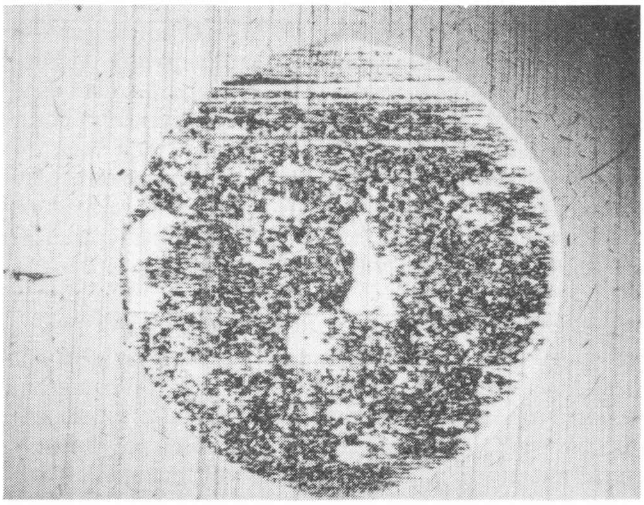


Figure 4 – Micrographs of the wear scars developed with fuel 5 at different relative humidity values

The increase in scar size and change in appearance of the oxide layer with increasing RH can probably be explained by the following mechanism. At higher RH (and atmospheric oxygen content) the scar surface oxidation rate is increased and the surface oxide layer requires a shorter period to reach a critical thickness where breakdown of the layer occurs under load. This causes exposure of the unoxidized metal and the more patchy appearance of the oxide layer. The detailed studies of other authors [1] have confirmed the oxidative nature of the wear mode in such boundary lubricated hydrocarbon systems, and they have also postulated similar wear mechanisms.

Wear rate as a function of applied load, determined at circumferential speeds of 0,1 and 0,5 m/s with fuels 1 and 5, is shown in Figs 5 and 6. All the determinations were made using a disc with a surface roughness of ~0,2 µm Ra and at 13% RH. The straight lines obtained indicate that the wear mechanism for each fuel was unchanged over the load range investigated.

The slopes of these lines represent the specific wear rates. As expected the specific rates differ for the two fuels under a single set of experimental conditions. However, at speeds of 0,1 and 0,5 m/s the slopes of the lines yield respective specific wear rates of 1,52 × 10^{-7} and 5,7 × 10^{-8} mm^3 N^{-1} m^{-1} for fuel 1 and 1,4 × 10^{-7} and 3,4 × 10^{-8} mm^3 N^{-1} m^{-1} for fuel 5. These results show that for both fuels the specific wear rate at 0,1 m/s is approximately three times higher than at 0,5 m/s. This decrease in wear rate with increased speed is probably associated with a change in wear mechanism due to different degrees of boundary lubrication. The suggested change in mechanism with test speed is substantiated by the fact that the wear scars generated at low speed show hardly any sign of the well developed oxide laywer visible on the scars generated at high speed.

Although the wear rate at 0,5 m/s is lower than at 0,1 m/s, larger wear scars were generated on the balls during testing at the high speed. This is not surprising, as the same running time (30 min) was used in all the tests, so that the sliding distance at the high speed was 5 times that covered at the low speed.

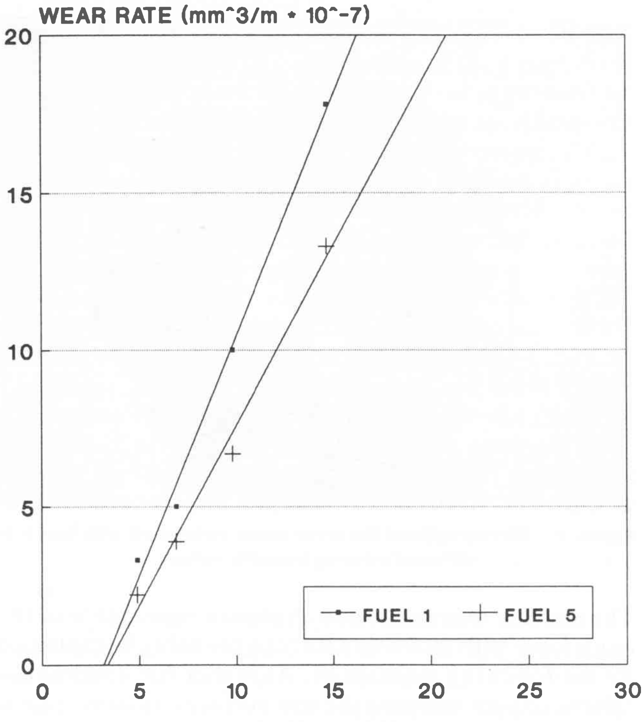


Figure 5 – The relationship between wear rate and applied load at 0,1 m/s

The purpose of the investigation was not only to gain some understanding of the influence of test variables on the lubricity behaviour of aviation fuels, but also to develop an in-house test which would yield results comparable with those from the BOCLE systems. The nine fuels used in this investigation had also been subjected to BOCLE testing in the USA.

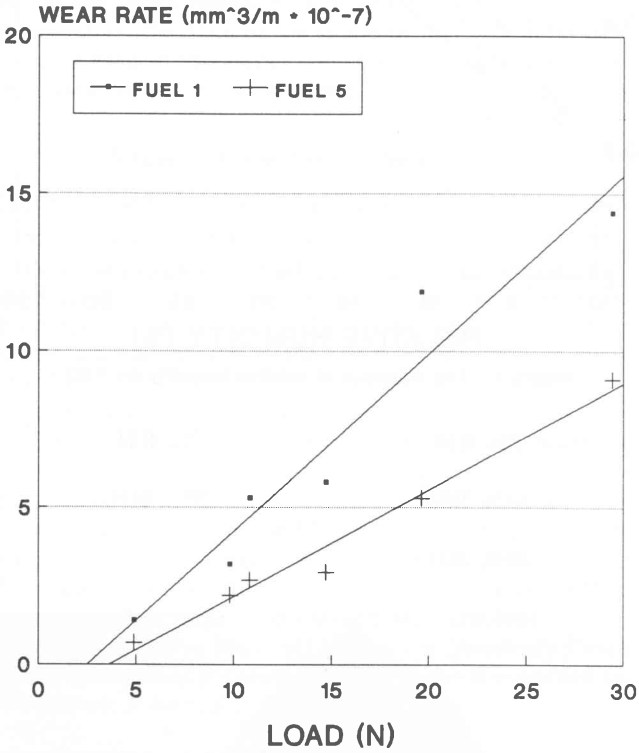


Figure 6 – The relationship between wear rate and applied load at 0,5 m/s

In Table 2, the BOCLE results are compared with two sets of results generated under different test conditions on the BOD equipment. It is interesting to note that the WSD resulting from the BOCLE test under a load of 9,8 N are larger than those obtained in the BOD-A test under a load of 14,7 N. These larger WSD can probably be related to three factors. Firstly the BOCLE rings (HRc 62) are much harder than the disc (HRc 36) used in the BOD test, and this may contribute to a higher wear rate. Then the surface finish on the rings (unidirectionally ground to a finish of ~0,6 µm Ra) is different to that of the disc (randomly sanded to a finish of ~0,2 µm Ra), and finally more fuel is available to act as lubricant in the fully flooded contact of the BOD test compared to the starved conjunction of the BOCLE test, which is only wetted by fuel transported from the bath on the ring surface. As the absolute WSD obtained with the different systems vary so much, the results are also listed after normalization with respect to fuel 5 for easier comparison.

Table 2 WSD generated with test fuels under different test conditions

Fuel	Wear scar diameters, mm					
	BOCLE	BOD-A 0,2 µm Ra 14,7 N 0,5 m/s	BOD-B 0,1 µm Ra 4,9 N 0,1 m/s	Normalized with respect to fuel 5		
				BOCLE	BOD-A	BOD-B
1	0,71	0,51	0,37	1,18	1,19	1,23
2	0,64	0,51	0,36	1,07	1,19	1,20
3	0,61	0,45	0,36	1,02	1,05	1,20
4	0,60	0,45	0,31	1,0	1,05	1,03
5	0,60	0,43	0,30	1,0	1,0	1,0
6	0,73	0,55	0,38	1,22	1,28	1,27
7	0,66	0,51	0,37	1,10	1,19	1,23
8	0,80	0,57	0,39	1,33	1,33	1,30
9	0,66	0,47	0,35	1,10	1,09	1,17

The results show that although the WSD obtained with the BOD equipment are appreciably smaller than those from the BOCLE test, the ranking with the two systems is very similar. This is also graphically illustrated in Fig. 7. As the contact geometries and test conditions used in the two systems are similar, the good correlation in results obtained is not unexpected.

The BOD test conditions under which the larger WSD are obtained (0,2 µm Ra disc, 0,5 m/s, 14,7 N load, 13% RH) are preferred as good reproducibility is much more readily achieved.

Conclusions

A ball-on-disc test method, operating in a controlled environment, has been successfully developed for the comparative evaluation of aviation fuel lubricity.

The influence of test variables such as surface roughness of the disc, test speed, applied load, test time and environmental relative humidity have been investigated. Their respective contributions related to the size of the wear scar have been established.

A comparison has been made between the results obtained with the BOCLE and BOD systems on nine aviation fuels. Although the absolute values of the WSD obtained with the two systems differ widely the lubricity rankings established correlate very well.

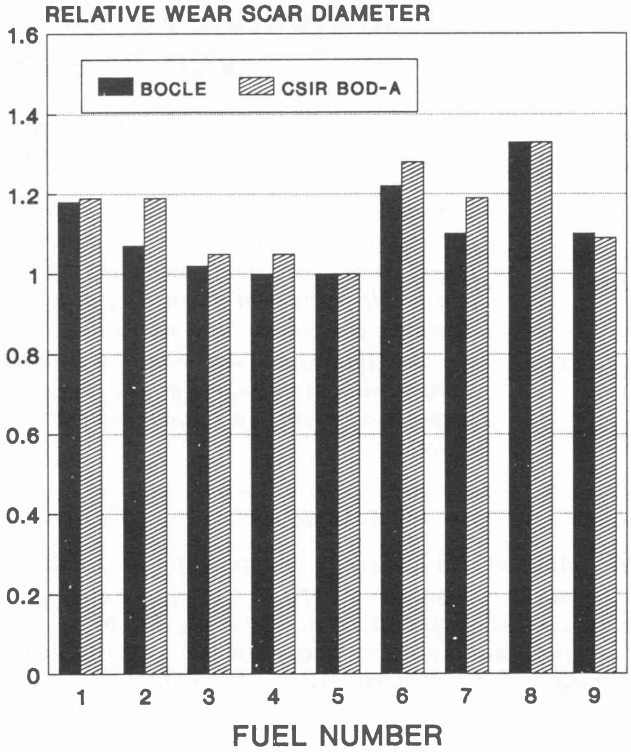


Figure 7 – Comparison of the relative WSD generated by the BOCLE and CSIR BOD-A tests

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