CRC Report AV-14-11

Aviation Turbine Fuel Lubricity - A Review

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COORDINATING RESEARCH COUNCIL, INC.
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1. Introduction

The Coordinating Research Council (CRC) offers the Aviation Industry an important forum to assess technical issues relating to aviation engines, airframes and fuels to promote flight performance and reliability across the world. As part of CRC activities, specific projects are sponsored to help the Industry gather data, undertake research and gauge technical impact. The current report relates to CRC Project AV14-11 which seeks to investigate aviation turbine (jet) fuel lubricity, bringing together a broad range of historical, current and specification knowledge. This is a particularly wide field of activity and focus has been placed on gathering data in 4 key areas:

(i) To identify which components in aircraft fuel systems/engines are most at risk from lubricity related wear problems.
(ii) To critically assess the test methods available to measure lubricity with respect to aviation fuel system applications.
(iii) Compare Defence Standard and ASTM approaches to jet fuel lubricity control for the current and potential future market.
(iv) Assess the control of lubricity in synthetic jet fuel components detailed in ASTM D7566.

In response the authors have sought information from a number of sources:

- Data and research used by the UK Ministry of Defence to include the lubricity requirement in Defence Standard 91-91 have been reviewed and reported.
- The aviation fuel lubricity research carried out during the 1980s and 1990s, in particular on behalf of the US and UK militaries, has been summarized.
- A literature survey has been carried out to identify any further information available.
- Lubricity and low sulfur related data from the CRC jet fuel sulfur survey and other available data such as Defense Energy Support Center (DESC), UK and USAF surveys have been summarized.
- Fuel purchasers, in particular, U.S. airlines, through Airlines 4 America (A4A), have been asked for their perception and experience of lubricity on product performance.
- Major engine equipment manufacturers (OEMs) and critical parts manufacturers have been consulted regarding their view of current fuel lubricity and the 0.85 mm Ball on cylinder lubricity evaluator (BOCLE, ASTM D5001) wear scar limit featured in some specifications.

For clarity information is presented in the following order:
Lubrication and Wear
Jet Fuel Lubricity
Operational Incidents
Laboratory Test Methods
Fuel Production Technology and Properties Affecting Lubricity
Lubricity Data on Production Fuels
Lubricity in Jet Fuel Specifications
Additives

2. Lubrication and Wear

For reference purposes, a brief introduction to tribology fundamentals is presented to define the lubrication-related terms recurring throughout this report. The theoretical background is limited to the operating conditions pertaining to turbine engine fuel systems.

The purpose of lubrication is to separate loaded, moving bodies by interposing a lubricant between their rubbing surfaces, to reduce friction and protect them against wear. Depending on the thickness of the lubricant film, different lubrication modes can be distinguished:

Hydrodynamic
For sliding surfaces, when the film of lubricant is thick enough, a wedge develops that forces the surfaces apart during relative motion so that the opposing surfaces are physically separated. This condition is identified as hydrodynamic lubrication. Since there is no contact between asperities on the surfaces, wear processes cannot take place.

Elastohydrodynamic
Elastohydrodynamic lubrication is similar to hydrodynamic but occurs when the surfaces are in a rolling motion (relative to each other). The film layer in elastohydrodynamic conditions is much thinner and the pressure on the film is greater. It is called elastohydrodynamic because the pressure on the film elastically deforms the rolling surface to lubricate it.

Boundary
A different situation arises when conditions produce a very thin film of lubricant, with thickness less than the dimensions of surface asperities (irregularities which form peaks and valleys at a microscopic level). Now metallic contact between the asperities of the rubbing surfaces can occur, leading to wear of the material. This is termed boundary lubrication. The lubricating film can be so thin as to contain only one or two layers of molecules. The chemistry of the lubricant plays the most important role. Friction and wear behaviour in this regime are determined by physical and chemical interactions at the metal interface.

Mixed
In the mixed regime, which is between the elastohydrodynamic and boundary lubricating regimes, the lubricant exists as either a full or a partial film between the surfaces. In this instance the load is carried partly by the fluid film and partly by the contacting surfaces. A mixed lubrication regime can occur in aviation fuel systems and is discussed further in Section 3.

Actual wearing away of material from (fuel) lubricated rubbing surfaces can take place by different mechanisms, of which the most common are:

Corrosion
Corrosion wear is attack of surfaces by oxygen and water present in the fuel to form metal oxides/hydroxides. These can be removed by rubbing and thus lead to wear. Dominated by chemical reactivity, this type of wear can be avoided by a film-forming additive such as a corrosion inhibitor that prevents oxidation of the surface.

Abrasion
Abrasion wear occurs when one surface comes into contact with another, significantly harder surface. Surface damage can be caused by grains of wear debris within the contact gap, and by oxide particles formed by corrosion, which are harder than the metal and give abrasive wear.

Adhesion
Adhesion wear happens when the protective lubricating film is absent, giving metal to metal contact. If frictional heating has raised the surface temperatures high enough, local welding (on a micro scale) can occur. The resultant tearing of the metal gives high friction and severe ‘scuffing type’ wear.

3 Jet Fuel Lubricity

Aircraft fuel systems contain pumps and fuel control units (FCUs) which rely on the fuel being pumped as the lubricant for their moving parts such as gears, pistons, sleeve valves, bearings, splines, etc. The effectiveness of jet fuel as a lubricant in such equipment is referred to as its 'lubricity'. The Aviation Industry aspires to understand and optimise this close link between fuel and hardware to benefit system reliability.

Depending on their design and the construction materials used, fuel pumps and FCUs will vary in their sensitivity to fuel lubricity. Similarly, depending on their composition, jet fuels vary in their capability to lubricate. Since the 1960s there have been sporadic occurrences of lubricity problems in which fuel system components have suffered excessive wear or seizure, which in the most severe cases has led to engine shut-down.

During the last forty years an enormous amount of research and development has been conducted by equipment manufacturers, fuel and additive suppliers, and military research organizations. The result of this research is that fuel system lubrication and wear mechanisms have been proposed, lubricity measurement devices have been developed, influence of fuel chemistry has been studied, specifications for lubricity improving additives (LIA) have been written, and fuel lubricity is specified for component testing.

3.1 Wear of Aircraft Fuel System Hardware

Some components of aircraft engine fuel systems, such as pumps and control units, rely on the fuel itself to serve as the lubricating medium between moving contact surfaces, and thereby reduce friction and wear. Kerosine fuel (unlike conventional lubricants that are formulated for the purpose) cannot produce a continuous hydrodynamic film, so that these components will normally operate in the boundary lubrication regime, or in the ‘mixed’ regime between the two extremes. In the mixed regime the lubricant exists as either a full or a partial film, the load being carried partly by the fluid film and partly by the contacting surfaces.

Under steady state conditions, a properly designed and run-in pump operates in the full-film mixed lubrication regime, where little wear would be expected. Components such as gear teeth only become vulnerable to excessive wear when operating in the boundary lubrication regime, and then only if insufficient lubrication is provided by the fuel, i.e. if the fuel has low 'lubricity[1]'. This type of situation can occur rapidly under certain critical conditions of speed, load and temperature.

Lubrication breakdown between rubbing components can in practice lead to mechanical failure of equipment, caused for example by excessive wear (adhesive, corrosive or abrasive) or by seizure (welding). In the days when piston pumps were used in turbine engines, failures due to lack of lubricity resulted in broken pistons as well as occasional piston/bore seizures. Pumping performance could be completely lost. The failure mechanism could be summarized by the sequence:

- high friction between the steel piston and bore surface caused high surface temperature on the steel piston, wear and ovalisation of the bore;
- reduction in fatigue resistance at the surface of the piston and the bending load due to ovalisation of the bore caused circumferential cracking and fracture of the piston.

Gear pumps are used on most modern aircraft and those suffering from low lubricity fuel problems have generally not failed catastrophically; instead their rate of wear has been accelerated, with consequent shortening of service life requiring premature replacement of the unit. Datschefski reported[2] that the failure mechanism of a pump can involve the following processes:

- scuffing wear of the gear tooth flanks, resulting from metal to metal contact with insufficient lubrication.
- gradual modification of the tooth profile, leading to surface fatigue and flaking of the contact surface.
- pulsing or hammering being induced, eventually causing damage to the gear shaft and bearings.
- cavitation erosion taking place on gear teeth and bearing bores.

Lacey et al.[3] reported that although some studies indicated that wear on failed aviation components was due to a scuffing mechanism following breakdown of the boundary lubricating film by the fuel, after further research, the most satisfactory explanation was a simple corrosive wear process. This involving the repeated formation and removal of metal oxides during sliding. It was concluded that, for aviation equipment, oxidative corrosion appeared to be the primary wear mechanism, followed by severe adhesive wear and scuffing as the component dimensions were reduced beyond tolerable limits. Lacey et al. went on to state that the secondary importance of scuffing is indicated by the fact that corrosion inhibitors have little effect on scuffing resistance, but are still capable of eliminating lubricity problems in aviation fuel systems.

3.2 Section Summary

- Kerosine cannot produce a continuous hydrodynamic film so aviation components normally operate in the boundary lubrication regime or in the mixed

[1] Sometimes fuels with low or poor lubricity are termed "hard".
[2] G. Rickard and G. Datschefski, "Lubricity Review,", Technical report to UK MoD DERA/MSS1/CR990253, January 1999.
[3] P. I. Lacey and S. A. Howell, "Fuel Lubricity Reviewed," l, SAE Technical Paper 982567, October 1998.

regime where the load is carried partly by the fluid film and partly by the contacting surfaces.

- The most likely explanation for wear in aviation systems is a simple corrosive wear process later followed by severe adhesive wear and scuffing as the component dimensions become reduced beyond tolerable limits.

4 Operational Incidents

4.1 Historical Problems

The first recorded field problem attributed to insufficient lubrication being provided by the fuel occurred in 1965, on US Air Force fighter aircraft flying on JP-4. On a number of different aircraft and engines, pilots experienced a lack of response from the fuel control lever when trying to decelerate. Cause of the failure was traced to sticking servo valves that were malfunctioning due to low lubricity of the fuel[4]. The fuel had been clay-filtered before use, thus removing any natural lubricating agents. Prior to this time corrosion inhibitor additive had been mandatory in JP-4/JP-5. When experience showed that lubricity was restored by the presence of this additive, mandatory addition was re-instated in JP-4 with issue of Amendment 1 to MIL-T-5624G, November 1966. Further details are documented by Martel, Bradley et al [5]. Due to concerns over the impact of the corrosion inhibitor on water separation/related issues, this was not extended to JP-5 until revision L of MIL-T-5624 in January 1985. Further occurrence of this particular problem was thereby prevented and an effective additive identified.

During the late 1960s, a series of lubricity-related field problems surfaced in Europe, connected with piston-type fuel pumps. Airlines had already accumulated many millions of flying hours on turbine engine piston pumps without experiencing any problems associated with lack of lubrication. Around this time, however, European refineries began to use hydrotreating to process jet fuel, and this was considered to be a contributing factor in bringing some lower lubricity fuels onto the market. Instances of pump failure began to appear, caused by heavy and rapid bore wear due to poor lubrication, cracked pistons, and even occasional piston seizure. Similar problems were reported on different aircraft by a number of operators[6], for example:

- on Draken fighters using JP-4 fuel (Royal Swedish Air Force)
- on Caravelle aircraft flying on Jet A-1 (Alitalia) and on Jet B (Sabena)
- on BAC Super 1-11 aircraft using Jet A-1 (BEA)

All of these operating problems were overcome by either adding corrosion inhibitor, where it had not been used before, or modifying the metallurgy of the pumps, e.g. substituting carbon sleeves for cadmium plating in piston bores.

Around 1975, the US Navy experienced problems involving a hang-up in the fuel control of the TF30-P-408 engine in A-7B aircraft[7]. Once more the problem was alleviated by

[4] D.L. Jun, "The Effects of Corrosion Inhibitor Content in JP-4 Fuel on J65W7D TJ-L2 Fuel Control Operation," Bendix Report No BPAD-863-16833R, July 1966.
[5] C.R. Martel, , et al., "Aircraft Turbine Engine Fuel Corrosion Inhibitors and Their Effects on Fuel Properties," AF Aero Propulsion, Laboratory Report, AFAPL-TR-20, July 1974.
[6] T.C. Askwith, P.J. Hardy, and R.A. Vere, "Lubricity of Aviation Turbine Fuels," Second Report of the MOD(PE) Fuel Lubricity Panel, Ref. AX/395/014, Jan. 1976.
[7] G. Rickard and G. Datschefski, "Lubricity Review," Technical report to UK MoD DERA/MSS1/CR990253, January 1999.

corrosion inhibitor, Hitec E515, which was added to fuel on-board carriers deploying these aircraft.

From the 1970s onwards the use of gear pumps increased to the extent that they became standard for most turbofan engines. These pumps are generally less vulnerable to the normal variations in fuel lubricity, however, isolated incidents of high wear have been observed. In Europe, several airline operators experienced problems with the TRW gear pump in JT-9D engines of the Boeing 747 in the early 1970s. The basic failure mechanism associated with lack of lubrication appeared to be scuffing causing heavy wear of gear teeth, leading to 'flatting' of the gear profile, followed by bearing wear and subsequent failure of the spline drive[8].

A similar problem came to light in the 1980s. Cases of pump failures in Rolls-Royce RB-211 engines again took the form of gear tooth scuffing wear, which in turn induced vibration, severe bearing erosion and spline damage. A characteristic feature of these operating failures was their geographically localized nature, aircraft operating in the Middle East having a third of the pump lives of their North American counterparts[9]. A remedy was brought about by pump modifications, such as improvements in gear tooth profiles and materials, and redesign of spline sections.

About the same time, gear pump problems on the CF6 engine turned up in Europe. Similar to those found on the RB-211, they were associated with specific airlines and even with specific engine positions. One of the affected operators was Lufthansa, who experienced five in-flight shutdowns of these pumps on Boeing 747s between 1979 and 1981. A dedicated fuel system was organized at Frankfurt airport to provide injection of Hitec E515 additive at each aircraft refuelling, and this helped to solve the problem. Design modifications made by the pump manufacturer ensured that similar failures did not recur.

Military vigilance continued with a major evaluation of corrosion inhibitors as lubricity improvers being undertaken by the US Air Force Wright Aeronautical Laboratories in conjunction with Pratt and Whitney[10]. This sought to:

- Evaluate currently approved corrosion inhibitors for lubricity enhancement.
- Determine minimum effective concentration/performance curves.
- Seek how a lubricity requirement might be incorporated into MIL-I-25017.
- Refine the Reverse Phase High Performance Liquid Chromatography method for determining the concentration of corrosion inhibitors in jet fuel.

In addition, for the specialty military fuel JP-7, a proprietary lubricity additive was developed to Pratt and Whiney Aircraft specification PWA-536 based on fuel pump endurance tests at 149 °C[11].

The next major field incident took place in New Zealand in the early 1990s. This was an unusual situation where the only fuel available throughout the country was produced by

[8] "C.A. Moses, L.L. Stavinoha, and P. Roets, "Qualification of SASOL Semi-Synthetic Jet A-1 as Commercial Jet Fuel," Report SwRI-8531, , Nov. 1997.
[9] G. Datschefski, "History, development and the status of the ball-on-cylinder lubricity evaluator for aero gas turbine engines," MoD Contract AE12a/193, March 1991.
[10] T. B. Biddle and W.H. Edwards, "Evaluation of Corrosion Inhibitors as Lubricity Improvers," AFWAL-TR-88-2036, July 1988.
[11] C. Martel, "Military Jet Fuels, 1944 – 1987," AD-A186 752.

the single refinery at Marsden Point. Domestic carriers operating only internal flights thus had a constant diet of the same quality fuel. Any production of poor lubricity fuel would be undiluted with better lubricity “softer” fuels from other sources. Service difficulties began in 1992 with Ansett NZ aircraft reporting premature spline-drive wear in fuel-lubricated fuel control units (FCUs). Air Nelson aircraft then also started to be troubled with similar problems [12]. Excessive wear was found in spline-drives connecting the fuel pumps to the FCUs of three manufacturers:

- Hamilton Standard, fitted to General Electric CT-7 engines on Saab 340s;
- Woodward, fitted to Allied Signal Garrett TPE-331s in Fairchild Metroliners;
- Lucas, fitted to Textron Lycoming ALF502R-3 engines on British Aerospace 146s.

Numerous removals from service were required due to these failures, which caused several shutdowns and in-flight failures of engines. Some splines, which should have had a service life of 3,000 to 5,000 hours, were wearing out after only 150 hours.

Actions were taken on several fronts to resolve the above problems: operators evaluated the use of an approved lubricity additive as a palliative; the component manufacturers set about improving their product design; and the refinery undertook measures to improve product lubricity. All aspects of this situation were debated at an industry seminar in 1994, convened by the CAA of New Zealand[13]. The refinery began adding approximately 5% straight-run kerosine to the hydroprocessed product, with the result that the lubricity of fuel produced steadily increased such that the Ball-on-Cylinder Lubricity Evaluator (BOCLE) wear scar diameter (WSD) decreased from a range of 0.75 – 0.85 mm to 0.60 - 0.70 mm when tested by ASTM D5001. No new lubricity related problems have been reported for this fuel.

[12] G. Rickard and G. Datschefski, “Lubricity Review,” Technical report to UK MoD DERA/MSS1/CR990253, Jan.1999.

[13] Aviation Jet Fuel Lubricity Seminar, CAA of New Zealand, Wellington, Sept. 1994.

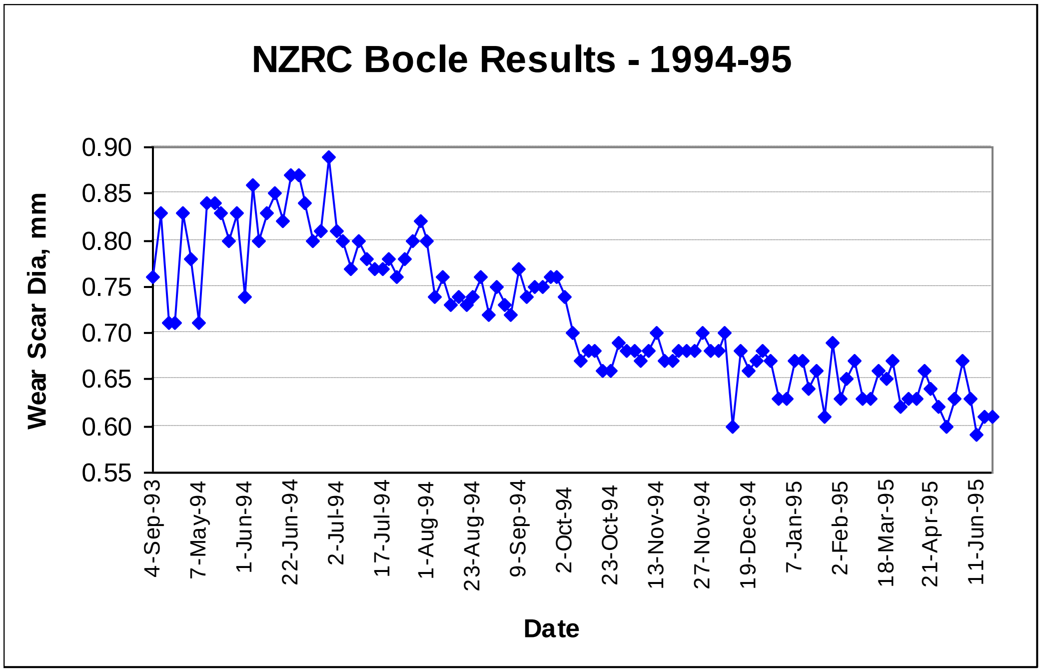

Figure 1: Fuel lubricity measured at the Marsden Point, New Zealand refinery

Japan Airlines, JAL, observed fuel pump failures on flights between Japan and Australia, beginning in 1995. The problem on JT-9D engines seemed to be aircraft specific, occurring on DC10s and Boeing 747s, and was attributed to fuel lubricity. However, the measured lubricity range of fuel samples was not unusual (WSD 0.6 mm - 0.8 mm). Pump modifications were instigated to effect a solution.

In all of these reported situations of excessive wear, the contributing factors were hardware design and suspected low lubricity fuel, typically uplifted from a fixed source of supply. Injection of lubricity-improving additive into the fuel was often used as a short term solution together with changes to refinery blend formulation. However, generally it was the mechanical modifications made by the hardware manufacturers that reliably prevented recurrence of such problems.

4.2 Current Experience

Engine and airframe Original Equipment Manufacturers (OEMs) and airlines were questioned about their recent experiences of lubricity problems.

4.2.1 Airlines

International Air Transport Association (IATA), Airlines 4 America (A4A) and individual airlines were contacted. Recent airline experience of lubricity problems proved difficult to obtain. Industry knowledge of the potential problems was not very extensive. Those airlines which replied reported no lubricity related problems in the field in the past five years.

4.2.2 Equipment and Airframe OEMs

OEMs[14] stated that fuel pumps are the critical areas of the fuel system with respect to wear and fuel lubricity. The metallurgy of pumps has been improved over the years and modern equipment is now less sensitive to fuel lubricity. However, some older equipment which may be more sensitive to fuel lubricity is still in use.

The general feeling expressed by OEMs was that all new equipment is now designed to operate with fuel having a BOCLE WSD of up to 0.85 mm, and is tested to SAE ARP1797 to ensure adequate durability. They believe that a 0.85 mm max BOCLE WSD is an acceptable upper limit for lubricity, but the average lubricity of jet fuel may need to be well below this limit (indeed one stated below 0.75 mm WSD) to ensure longevity of equipment. Some older engines/fuel pumps have a 0.65 mm max BOCLE WSD to provide extended pump life, and addition of Corrosion Inhibitor/Lubricity Improver (CI/LI) additives to low lubricity fuels is recommended by the manufacturers.

Small engines (business, regional, general aviation, helicopters) were reported to be more likely to get a steady diet of a low lubricity fuel than engines used on large commercial transport aircraft, as shown by the New Zealand incident, because of their tendency to fly from fixed bases.

Three out of four OEMs interviewed supported the jet fuel lubricity requirements set out in Defence Standard 91-91, detailed in Section 7 of this report, as a useful route to controlling hardware related incidents. However fuel survey data, Section 7, also indicated good lubricity coverage with current specifications wording and production routes.

4.3 Section Summary

- The Military have played a major role in identification of lubricity as an operational issue and the assessment of additives to remediate risk.
- There have been isolated incidents caused by poor fuel lubricity since the middle 1960s, the most serious of which was in New Zealand in the early to mid 1990s. There do not appear to have been any reported fuel related lubricity issues in the past five years.
- Lubricity problems have been overcome by use of additives, aircraft fuel system hardware changes or by blending fuel to give better lubricating ability.
- Engine OEMs stated that fuel pumps were the critical component with respect to fuel lubricity. Some older equipment which is more sensitive to fuel lubricity may still be operational but modern equipment is designed to operate on fuel of BOCLE WSD up to 0.85 mm.

[14] E-mail responses to questions were received from Rolls Royce, Pratt & Whitney, GE and Honeywell. These OEMs were happy to speak on behalf of their component suppliers.

5 Laboratory Test Methods

5.1 History of Equipment Development

Since the 1970s a variety of mechanical rig tests have been devised to measure the lubricating performance of aviation fuels. The impetus for their design generally arose from the need to simulate and investigate operating problems that had occurred in service with specific engine hardware. Many of these rigs were of limited manufacture, built and operated only within a few company laboratories, but they have nonetheless yielded much valuable research data about lubricity properties. Examples are the Bendix Spool Valve Lubricity Tester, the Esso Pin-on-Disc rig, and the Thornton Aviation Fuel Lubricity Evaluator. Only two testers gained wide acceptance throughout the industry, and were built in some quantity: the Dwell Tester and the Ball-on-Cylinder rig.

5.2 Bendix Lubricity Simulator

'Stiction' of fuel controls on USAF military aircraft resulting from poor lubrication was one of the earliest reported field problems. In response, Bendix developed a fuel control simulator to measure how long a fuel-lubricated sliding valve would operate before sticking occurred. The coefficient of friction attained during a test was used to define the lubricity quality of a fuel. Co-operative testing was carried out by Bendix, General Electric and the USAF under the aegis of the CRC Fuel Lubricity Group. Later the Simulator was used with hardened steel test elements to rate a series of jet fuels that were also evaluated on the Exxon Ball-on-Cylinder (BOC) rig. Good agreement was found between the results from the two devices. This contributed to the demise of the Bendix Simulator, for at the time the BOC rig was rapidly gaining acceptance as the best available lubricity tester.

5.3 Esso Pin-on-Disc Rig

Based on the Ball-on-Cylinder machine, this rig could use various metallurgies to measure wear rate, friction and metallic contact with light loads that assured operation in the region of boundary lubrication for kerosine fuels[15]. The most effective configuration had a silver-plated pin riding on an S15 steel disc. This represented the slipper pad/cam-plate metallurgy of the Lucas piston pump. Test results established different wear rates between hydrotreated and chemically treated fuels; the lubricating power of corrosion inhibitor additives, and the benefits of blending different types of production fuels.

One way of introducing a lubricity requirement into DERD[16] fuel specifications was considered to be via a chemical test to measure the active lubricity constituents in a fuel. Much of the work on the Pin-on-Disc rig was focused on the identification of the naturally occurring lubricity agents in turbine fuels. The two chemical species having the most significant effect on lubricity were discovered to be naphthalenes and sulfides. However, specific compounds and interactions between the species were never fully determined.

It was then decided that a realistic lubricity test must apply to all fuel systems, including gear pumps, and experiments were extended to evaluate effects of fuels in a steel-on-

[15] R. Vere, "Lubricity of aviation turbine fuels," SAE Technical Report 690667, Oct. 1969.
[16] DERD specifications were the forerunners of the current UK MoD Defence Standard specifications.

steel metallurgy. Results again showed a correlation with naphthalene content, but not with sulfides[17]. Due to the anomalous results obtained with different metallurgies it was not possible to select any test parameters as the basis of a specification test method.

5.4 Thornton Aviation Fuel Lubricity Evaluator

Shell Research at Thornton, UK, began evaluating fuel lubricity properties on an Amsler T135 wear tester, an apparatus having two vertically-mounted, cylindrical specimens, their contact area being lubricated by a continually replenished stream of fuel. One cylinder was rotated and the other held stationary so that wear scars were ground into it. During a test, increasing increments of load were applied, each for a fixed period of time, until scuffing or seizure took place. At each load stage, the stationary specimen was turned a little to expose a fresh part of the surface, thus producing individual wear scars that could later be examined for evidence of scuffing. Results were so promising that around 1970 a modified version of the machine was built and dubbed the Thornton Aviation Fuel Lubricity Evaluator (TAFLE). This gave considerable discrimination between low and high lubricity reference fuels. Furthermore, the addition of corrosion inhibitors to the low lubricity reference fuels produced a substantial reduction in the coefficient of friction.

With time, several more versions of the TAFLE apparatus and test procedure were developed. Similar in principle, the evolved procedures differed with respect to fuel supply, environment and specimen metallurgy, surface finish and hardness[18]. Details of the Mark IV method were published in 1985, and this was in turn superseded by later in-house developments. The quality of a fuel's lubricity measured on the TAFLE was reported as a failure load (in kg), representing the load at which scuffing takes place. For a set of fuels representing a broad spectrum of compositions, typical failure loads ranged from 50 to 150 kg. Two basic criteria were used to define the failure load: the load at which the coefficient of friction reaches a value of 0.4, and the load where welding was observed in the wear scar. Friction failure load was considered to be the best criterion for measuring the lubricity properties of aviation fuels, giving excellent discrimination between fuels of differing lubricities and good correlation with data for piston pump life.

Bauldreay et al.[19] reported a one-off test using a gear pump rig that ran for 6-8 hours before fuel pump components were inspected for evidence of wear. The tests that were run indicated a good correlation between the rig and the TAFLE results.

5.5 Lucas Dwell Tester

The 'Dwell Tester', developed by Lucas Aerospace Ltd, had a noteworthy period of popularity in the 1970s. The rig was initially designed to represent the metallurgy of the Lucas piston pump which was then widely used on British engines, and which had experienced low lubricity fuel performance issues. Contact was between an aluminium bronze pin (pump bores) rubbing on a steel disc (pistons). During the test, a pin was loaded onto the slowly rotating horizontal disc, covered with a thin film of fuel. Friction

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[17] T.C. Askwith, P.J. Hardy, and R.A. Vere , "Lubricity of Aviation Turbine Fuels," Second Report of the MOD(PE) Fuel Lubricity Panel, Ref. AX/395/014, Jan. 1976.

[18] J.W. Hadley, "A Method for the Evaluation of the Boundary Lubricating Properties of Aviation Turbine Fuels," *Wear*, 101 (3), pp219-253, 1985.

[19] J.M. Bauldreay and C-H. Ang, "Reduced Sulfur Aviation Fuels – A Worldwide Challenge." IASH 2003, Steamboat Springs, Colorado.

increased as the boundary layer was removed, and the number of revolutions taken by the disc to reach a specified friction coefficient was called the dwell number[20]. The underlying principle of the test was therefore not to measure wear, but to investigate the resistance to breakdown of the boundary film of fuel.

The UK Ministry of Defence (MoD) Lubricity Panel decided to evaluate the Dwell Tester as a possible mechanical rig which could be used to specify lubricity limits for aviation turbine fuel. Representatives of various laboratories formed a Dwell Test Operators Sub-Panel to evaluate the device. Considerable efforts were taken to establish a standard test procedure, but the results for repeatability and reproducibility were very disappointing. In the US, the Dwell Tester was also investigated by members of the CRC Aviation Fuel Lubricity Group. Because of its demonstrated shortcomings, it was agreed that the test could not be considered as a standard method at that time.

An adaptation of the Dwell Tester was undertaken by the American component company TRW[21]. They made various changes to the test method and hardware. Friction measurements obtained by this revised approach yielded good agreement with experimental gear tooth wear data. Lubricity of more than 600 fluid samples was measured over 2 years, mostly in support of aviation fuel pump testing.

5.6 Ball-on-Cylinder Tester

The first Ball-on-Cylinder (BOC) rig was developed in 1965 by Exxon Research under a USAF contract arising out of their lubricity field problems. The basic device consisted of a ½ inch diameter steel ball loaded against a rotating steel cylinder which was partially immersed in a fuel reservoir. Wear took place at the point of contact between the two specimens, the area being continuously lubricated by a thin film of fluid from the reservoir. Design of the equipment (originally devised for evaluating mineral lubricant) was such that metallurgy, cylinder rotating speed and loading could all be varied, so that the entire region from hydrodynamic to boundary lubrication could be investigated. For studying jet fuels, a fixed set of running conditions were set up, which have remained essentially unchanged since that time. Initially, lubricating performance was measured by the degree of friction between the rubbing surfaces, but it was soon found that the WSD on the ball was a more sensitive and reliable indicator. Size of the WSD became the definitive assessment of a fuel's lubricity[22].

By the late 1970s nine BOC rigs were being operated in US laboratories, and UK operators were also starting to use them. A variety of BOC machines, test procedures and test cylinder metallurgies then existed among the different users, so that reproducibility of data between laboratories was being severely restricted by lack of standardization. The task of standardizing the basic test and establishing its precision was taken up by the CRC, under whose auspices a series of inter-lab test programs took place. It was to take many years of endeavour by operators on both sides of the Atlantic, and three round-robin analyses of fuel samples, to refine the test so that it gave results

[20] R.T. Aird, and S.L. Forgham, "The Lubricating Quality of Aviation Fuels," *Wear*, 18, pp361-380, 1971.
[21] C.S. Nau and W.K. Weinhold, "Fuel Lubricity Effects on Boundary Friction and Scoring Gear Tooth Wear in Aviation Fuel Pumps," Report by TRW Aircraft Components Group, Cleveland, Ohio, Apr. 1982.
[22] G. Datschefski, "History, development and the status of the ball-on-cylinder lubricity evaluator for aero gas turbine engines," MoD Contract AE12a/193, March 1991.

with acceptable precision. Details of the three CRC round-robins were chronicled and summarized in a 1988 report[23], with a test method appended. This report and test method was taken up by ASTM, and was accepted after two ballots. The method was published as ASTM D5001 in 1990. Standardization of the test apparatus came about indirectly, when the need arose to monitor the presence of lubricity additive in shale-derived JP-4 used by the US Air Force. Consequently, InterAv Inc. was contracted in 1984 to build a semi-automated version of the BOC - ten units being distributed to USAF airbases. The InterAv Model BOC-100 included an environmental control system providing regulation of air flow, humidity and temperature. The ball-on-cylinder part of the equipment was basically unchanged from the original design. InterAv units provided the foundation for the final successful CRC round-robin. A fully automatic method was latterly developed by PCS Instruments. The equipment, now known as the Ball-on-Cylinder Lubricity Evaluator (BOCLE), is almost universally accepted whenever the lubricity of aviation fuels is required to be measured. Further details are provided in Section 5.7 below.

5.7 Ball on Cylinder Lubricity Evaluator Standard Test Method

The Standard Test Method is fully described in ASTM D5001: Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE). This method was specifically developed for aviation fuel evaluation.

> *50 ml of test fuel is placed in a reservoir and maintained at 25°C under a controlled airflow at 10% relative humidity. A steel ball held in a vertically mounted chuck is forced against an axially mounted steel cylinder with an applied load of 1000 g. The test cylinder, which is partially immersed in the fuel reservoir, is rotated at 240 rpm. This maintains the cylinder in a wet condition and continuously transports fuel to the ball/cylinder interface. After the 30 minute test, the oval-shaped wear scar generated on the test ball is examined at 100X magnification under a microscope and its size measured, reporting the average of the major and minor axes as the (mean) wear scar diameter (WSD). Lubricating properties of a fuel sample are then assessed by the magnitude of its WSD. A semi-automatic test equipment and a fully automatic test equipment are available.*
>
> *Test precision for the semi-automatic method is defined by the formulae:*

$$\text{Repeatability} = 0.08311\ (WSD)^{1.5832}\ \text{mm}$$
$$\text{Reproducibility} = 0.1178\ (WSD)^{1.5832}\ \text{mm}$$

[23] "Aviation Fuel Lubricity Evaluation," CRC Report No. 560, July 1988.

Test precision for the fully automatic method is defined by the formulae:

$$\text{Repeatability} = 0.08580\ (WSD)^{2.5083}\ mm$$
$$\text{Reproducibility} = 0.09857\ (WSD)^{2.5083}\ mm$$

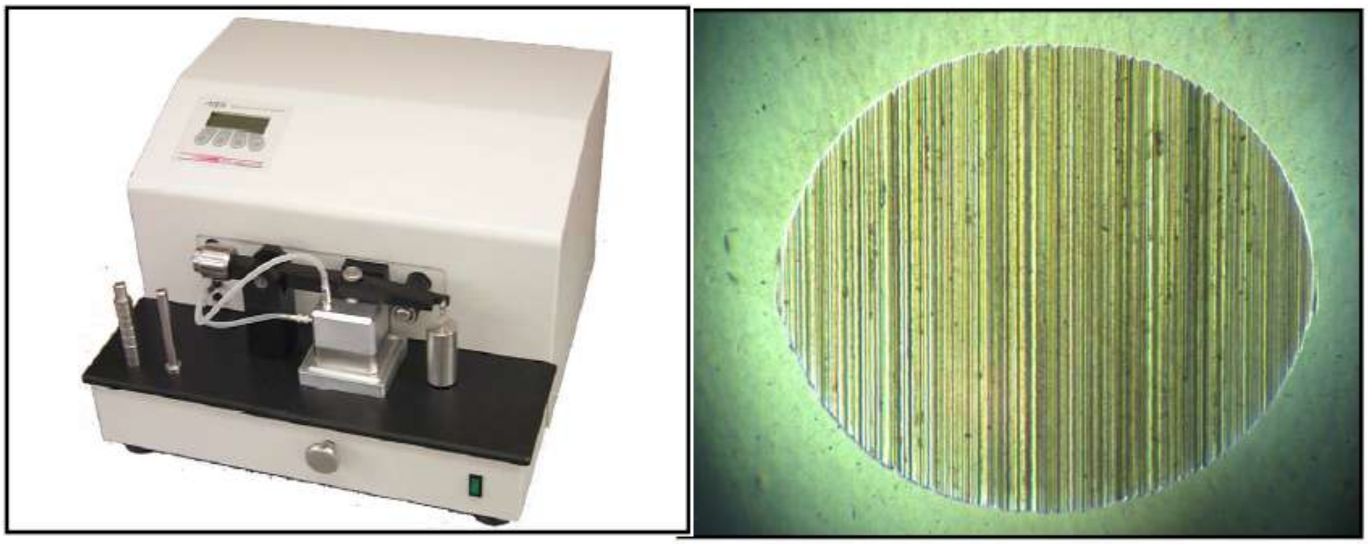

Figure 2: BOCLE apparatus and typical wear scar, courtesy of PCS Instruments.

Under ASTM D5001 conditions oxidative corrosion (mild oxidative wear) is the primary wear mechanism, though the rig also produces corrosive wear with higher, in specification, sulfur level fuels.

The BOCLE, as with most lubricity tests, is sensitive to:

- The metallurgy of the test pieces. The Ball and Cylinder must meet the requirements of ASTM D5001. For example the cylinder test ring must be manufactured of SAE 8720 steel, having a Rockwell hardness “C” scale, (HRC) number of 58 to 62 and a surface finish of 0.56 to 0.71 µm root mean square and be cleaned as directed.
- Trace components in the fuel. Care must be exercised to avoid contamination during sampling or from sample containers. ASTM D4306 gives some details of suitable equipment and practice. Furthermore, as a sample ages it may form trace compounds which can change the lubricity characteristics. Contamination or ageing tend to give false increased lubricity results.

5.7.1 Scuffing Load BOCLE (SLBOCLE)

The wear process found in the standard BOCLE test is primarily mild (oxidative) wear. However, some researchers recorded that failure of aircraft fuel pumps due to low lubricity fuel is generally caused by erosion of gear teeth by scuffing (adhesive wear). It has been reported[24] that standard BOCLE tests are generally not valid for assessing the scuffing performance of aviation fuels in gear pumps since the mild wear/scuffing wear correlation depends on fuel composition. The figure below shows a comparison of

[24] Aviation Jet Fuel Lubricity Seminar, CAA of New Zealand, Wellington, Sept. 1994.

TAFLE plotted against standard BOCLE results for a range of fuels. From this it was inferred that the standard BOCLE test is valid for comparing fuels of similar compositions, but could not be used to predict the scuffing performance of fuels.

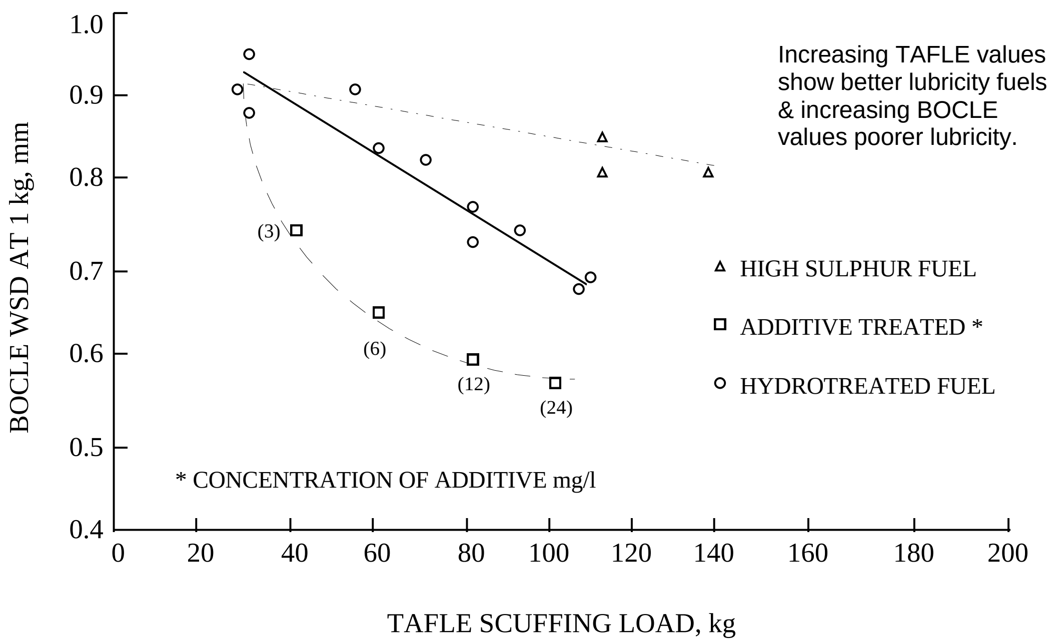

Figure 3: TAFLE Scuffing load plotted against BOCLE wear scar diameter[25]

Several scuffling BOCLE test methods were proposed during the 1980s and 1990s, one of these was briefly adopted in the UK lubricity additive specification, Defence Standard 68-251, but later abandoned due to lack of industry support.

A standardized test method, ASTM D6078, has now been developed and defines the evaluation of the lubricity of diesel fuels, certified as meeting ASTM D975, using a scuffing load ball-on-cylinder lubricity evaluator (SLBOCLE).

> *A 50 ml test specimen of fuel is placed in the test reservoir of an SLBOCLE and adjusted to the test temperature of 25°C. When the fuel temperature has stabilized, 50 % relative humidity air is used to aerate the fuel at 0.5 l/min while 3.3 l/min flows over the fuel for 15 min. During the remainder of the test sequence, the 50 % relative humidity air flows over the fuel at a rate of 3.8 l/min. A load arm holding a non-rotating steel ball and loaded with a 500 g mass is lowered until it contacts a partially fuel immersed polished steel test ring rotating at 525 rpm. The ball is caused to rub against the test ring for a 30 seconds break in period before beginning an incremental-load or a single-load test. Wear tests are conducted by maintaining the ball in contact with the partially immersed 525 rpm test ring for 60 seconds. For incremental load tests, the test ring is moved at least 0.75 mm for each new load prior to bringing a new ball into contact with the test ring.*

[25] Aviation Jet Fuel Lubricity Seminar, CAA of New Zealand, Wellington, Sept. 1994.

The tangential friction force is recorded while the ball is in contact with the test ring. The friction coefficient is calculated from the tangential friction force. In the incremental-load test, the minimum applied load required to produce a friction coefficient greater than 0.175 is an evaluation of the lubricating properties of the diesel fuel. In the single-load test, a friction coefficient less than or equal to 0.175 indicates the diesel fuel passes the lubricity evaluation, while a friction coefficient greater than 0.175 indicates the diesel fuel fails the lubricity evaluation.

The test method reports that the trend of SLBOCLE test results to diesel injection system pump component distress, due to wear, has been demonstrated in pump rig tests for some fuel/hardware combinations where boundary lubrication is believed to be a factor in the operation of the component, however no mention is made of using this test method with jet fuels. Although the SLBOCLE and High-Frequency Reciprocating Rig (HFRR, Test Method ASTM D6079) are two methods for evaluating diesel fuel lubricity no absolute correlation has been developed between the two test methods.

5.7.2 Elevated Temperature BOCLE

The standard 25 °C operating temperature used for running the BOCLE was chosen to optimize precision of test results in the laboratory, but this falls short of representing the considerably higher temperatures actually attained by fuel passing through aircraft engine systems, which may reach 100 °C or more. Running the test at a higher fuel temperature would therefore be a desirable objective for more realistic modelling of how changes in fuel lubricity affect engine component wear under practical conditions.

Elevation of temperature produced two opposing reactions in the BOCLE: initially an increase in wear and then, with continuing temperature increases, a decline in wear rate. One study used a fuel-recirculating BOCLE to measure changes in lubricity with increasing temperature[26]. The first phenomenon was a doubling of wear rate from 27 °C to 72 °C. This was attributed to reduction of fluid viscosity and weakening of the forces adsorbing the lubricating molecules onto the metal surface. At around 90 °C, WSD stopped rising and then continued to drop sharply as temperature was increased up to 180 °C. This was attributed to the formation of fuel oxidation products. Oxygenated species that were formed (e.g. aldehydes, alcohols, carboxylic acids, etc.) were all polar compounds that act as good lubricity agents.

Rolls-Royce[27] undertook a feasibility study of extending BOCLE operation up to temperatures of 150 °C. Again, wear was observed to rise with increasing temperature, then fall as competing anti-wear products began to be formed at higher temperatures. Most fuels exhibited a minimum lubricity peak between 80-120 °C. The figure below gives typical results. It was concluded that operation of the BOCLE at elevated temperatures was feasible, with test rig modifications including a heated fuel reservoir and heated test block.

[26] W.G. Dukek, and R.A. Vere, "Fuel Lubricity," IATA Fuel Symposium, Geneva, May 1971.
[27] S.P. Bullock,C. Lewis, and A. Hobday, "Application of Modified BOCLE to Determine Fuel Lubricity and Additive Behaviour at Elevated Temperatures," Presented at CRC Aviation Fuel Meeting, CRC Project No. CA-45-68, Apr. 1992.

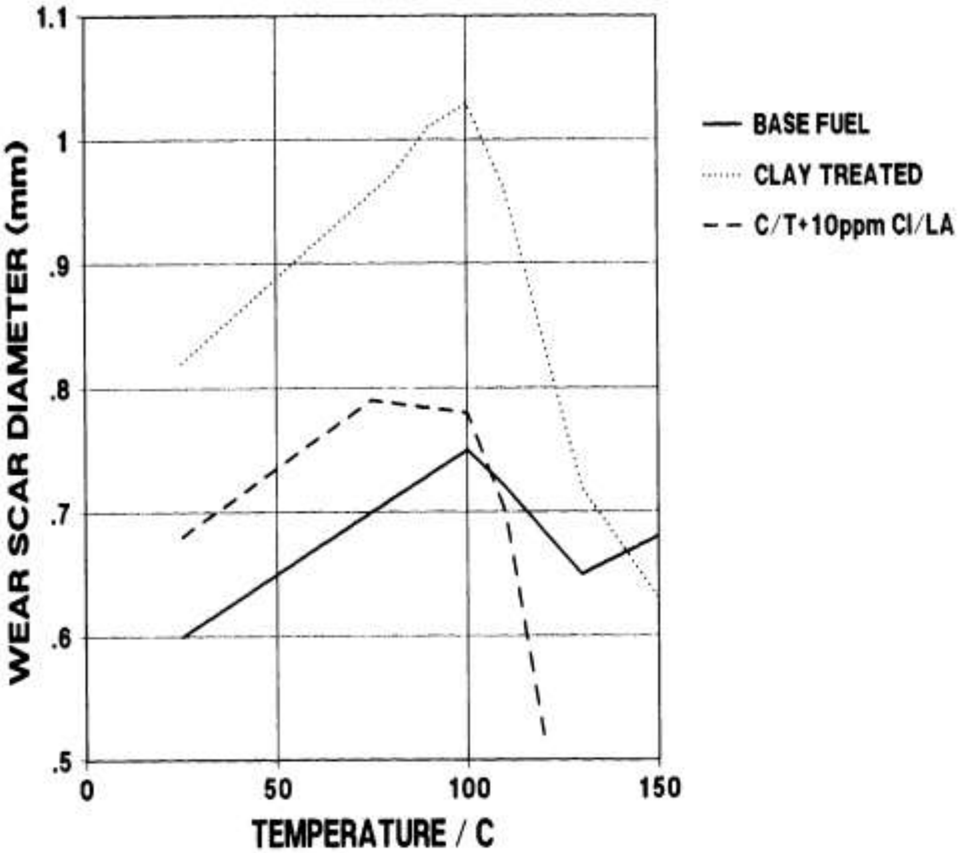

Figure 4: High Temperature BOCLE Results (Rolls-Royce)

High temperature lubricity results need to be interpreted with some caution, since the lubricating behaviour of fuels is influenced by many factors. Wear is directly affected by the concentration of surface active species in the boundary layer between the rubbing surfaces. These species include polar compounds naturally occurring in the fuel; purposely-added lubricity improvers; dissolved oxygen and water absorbed by fuel handling; and thermal/oxidative degradation products from the fuel. All of these species compete for adsorption on the contact surfaces of the test specimens. Thus wear protection given by a fuel at high temperature may be enhanced or degraded, depending on the equilibrium reached between adsorption and desorption of the various compounds at that temperature.

Biddle and Edwards[28] demonstrated that the performance of fuels treated with CI/LI additives was clearly affected by increased temperature. In an extensive investigation of corrosion inhibitor products, BOCLE wear scars generated at 75 °C were in most cases measurably larger than those at 25 °C, due to desorption of inhibitor from the metal surface. However, there was a random scatter of high temperature test results for many

[28] T.B. Biddleand W.H. Edwards, "Evaluation of Corrosion Inhibitors as Lubricity Improvers," AFWAL-TR-88-2036, July 1988.

additives. The study concluded that assessment of temperature effects on fuel lubricity was beyond the capabilities of standard BOCLE operation.

Water content of the fuel is an interrelated factor that must be taken into consideration when testing at different temperatures. Dissolved water has a profound effect on the corrosive wear mechanism in the BOCLE, giving rapidly increasing wear with increasing relative humidity of test air supply. Fuel at higher temperature will contain more water, since water solubility is a strong function of temperature.

5.8 High Frequency Reciprocating Rig

The High Frequency Reciprocating Rig (HFRR) has so far been used mostly for measuring diesel fuel lubricity. The test method development was largely driven by legislation forcing a reduction of sulfur resulting in diesel fuels having greatly reduced lubricating properties. Wear protection of fuel-lubricated injector pump components began to be jeopardised, in most cases requiring additive treatment to restore adequate protection of such equipment. It should be noted that:

- The method is more focused on reciprocating movement, as found in diesel injectors, rather than on sliding movement mainly featured in aviation fuel control.
- Metallurgy is different to reflect the two different applications.
- Additives which are responsive to HFRR can differ to those which improve BOCLE, again in agreement with the different wear regime.

The test rig, which can be seen in the figure below, consists of a steel ball loaded and reciprocated against a flat steel test plate. The contact is fully immersed in fuel contained in a temperature controlled bath. The ball is reciprocated using an electrical vibrator. The dimensions of the major and minor axes of the wear scar are measured under 100x magnification and recorded. Because the stroke length can be controlled over a very wide range, it is possible to carry out both adhesive sliding wear and ‘fretting’ wear tests using the same rig operating under different conditions. Fretting wear is a mixture of oxidative and abrasive wear caused by repeated movement over a small contact area; this was identified as one of the wear mechanisms found in rotary diesel fuel pumps.

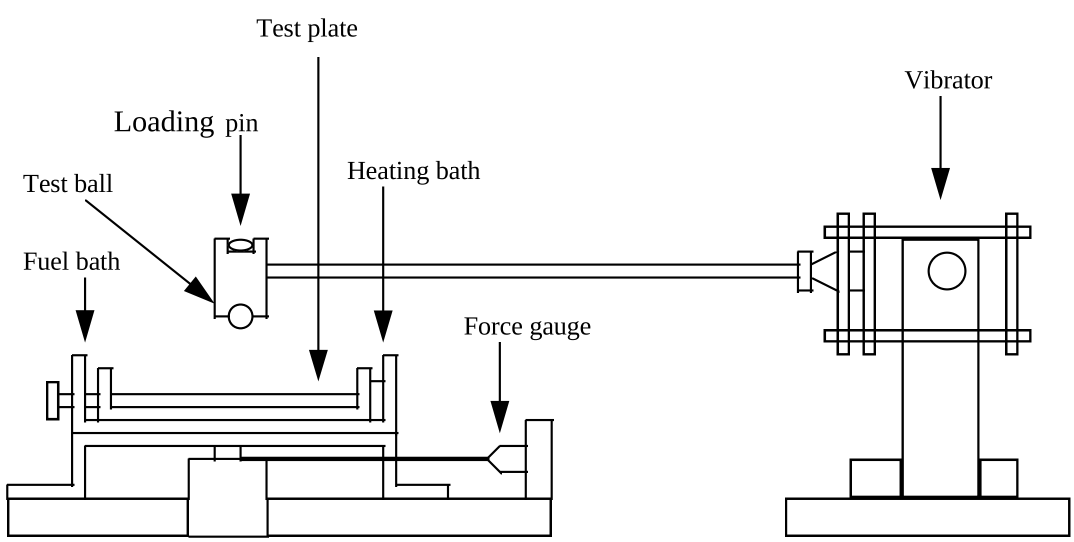

Figure 5: Schematic Diagram of HFRR

It is noted in the standard test method, ASTM D6079, that HFRR is not able to predict the performance of all additive/diesel fuel combinations[29].

The use of HFRR for jet fuel may be attractive due to its widespread availability, however, as the wear mechanisms are different to those observed with the BOCLE test, D5001, strong correlations are unlikely. Osman[30] reported a comparison of HFRR and BOCLE which showed no correlation, Figure 6. The red line on the chart represents the UK jet fuel specification limit.

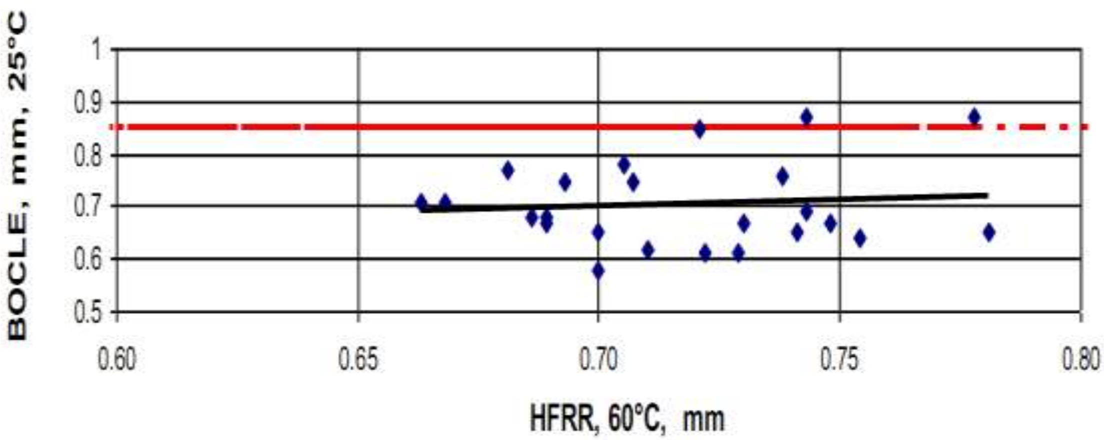

Figure 6: BOCLE wear scar diameter plotted against HFRR[30]

Much research on lubricity has been carried out by the US and UK militaries in support of the NATO single fuel policy, whereby jet fuel is used for powering ground equipment, using diesel engines, as well as aircraft. This has mostly concentrated on fuel pump wear in compression ignition engines fuelled with jet fuel. Automotive fuel pumps may not be representative of aircraft fuel pumps, nevertheless, some of the research data may be of relevance.

Frame et al.[31] tested synthetic (Fischer-Tropsch) JP-5 comparing fuel pump wear in a 6.5 litre diesel engine with a range of bench top lubricity tests. Tests using neat synthetic JP-5 showed significant wear on fuel pumps. Wear problems appeared to be eliminated by adding a jet-fuel type lubricity additive at 12 mg/l and 22.5 mg/l.

The bench top tests used were: BOCLE by ASTM D5001; SLBOCLE by ASTM D6078; HFRR by ASTM D6079; and Ball on three disks (BOTD). The SLBOCLE and HFRR did not detect the change in fuel lubricity level between the untreated and treated fuels and it was concluded that they lack the sensitivity to additives used at low concentrations. The

[29] D6079-11 – Standard test method for evaluating lubricity of diesel fuels by the high-frequency reciprocating rig (HFRR). ISO 12156 Part 1 / IP 450 is another HFRR method which is essentially the same as ASTM D6079.
[30] Jet fuel lubricity, study of sulfur content effect and test method, BOCLE vs HFRR. Ron Osman, Flint Hills Resources, CRC aviation committee meeting, May 2012.
[31] Alternative Fuels: Assessment of Fischer-Tropsch Fuel for Military Use in 6.5L Diesel Engine. E A Frame et al, SAE 2004-01-2961, October 2004.

BOCLE and BOTD along with the low frequency reciprocating rig (LFRR, Section 5.8.2) showed a better correlation with lubricity additized fuels. Although this research was connected with automotive engine fuel pumps it demonstrates that some tests are not sensitive to jet fuel lubricity additives.

Brandt et al.[32] undertook similar work featuring a 6.7 liter Scorpion diesel engine to evaluate Diesel versus Jet A containing 9 mg/l corrosion inhibitor / lubricity additive as approved for JP-8. Studies also included Jet A blended with synthetic paraffinic kerosene (SPK) at 50:50 and pure SPK. Interestingly results showed some agreement between HFRR and BOCLE data, Table 1. All fuels performed satisfactorily in the engine but further work was recommended.

Test	Units	Diesel	Jet A + CI/LI	50:50	SPK
HFRR D6079	mm	0.444	0.675	0.695	0.840
BOCLE D5001	mm	0.46	0.69	0.72	0.76

Table 1 HFRR and BOCLE Data for Diesel Engine Testing [32]

A more extensive study was undertaken by the U.S. Army which sought to determine the general applicability of jet fuels manufactured by alternative routes for use in ground equipment. A number of reports are available, for example Jeyashekar et al.[33], Willson III and Westbrook[34], Muzzell et al.[35]. These focus on synthetic paraffinic kerosene (SPK), hydroprocessed esters and fatty acids (HEFA) and alcohol to jet (ATJ), either in blend or pure. Test methods featured BOCLE, SLBOCLE and HFRR with blend composition, CI/LI additive type, concentration and performance evaluated. With respect to blend composition, blending SPK or HEFA with conventional jet was found to enhance lubricity. BOCLE showed good response for additives when tested in SPK and HEFA but HFRR proved insensitive. No correlation was apparent between BOCLE and HFRR based on a 6 sample/5 treat rate matrix, Table 7 [34].

[32] A.C. Brandt, et al.,, “Military Fuel and Alternative Fuel Effects on a Modern Diesel Engine Employing a Fuel-Lubricated High Pressure Common Rail Fuel Injection System,” NDIA Ground Vehicle Systems Engineering and Technology Symposium, Aug 2011.
[33] N. Jeyashekar, et al., “Lubricity and Derived Cetane Number Measurements of Jet Fuels, Alternative Fuels and Fuel Blends.” SwRI Interim Report TFLRF No. 405, July 2010.
[34] G.R. Willson III and S. Westbrook, “Distillate Fuel Trends: International Supply Variations and Alternative Fuel Properties,” SwRI Interim Report TFLRF No. 435, Jan. 2013.
[35] P.A. Muzzell et al.,”U.S. Army Qualification of Alternative Fuels Specified in MIL-DTL-83133H For Ground Systems Use,” Sept. 2013.

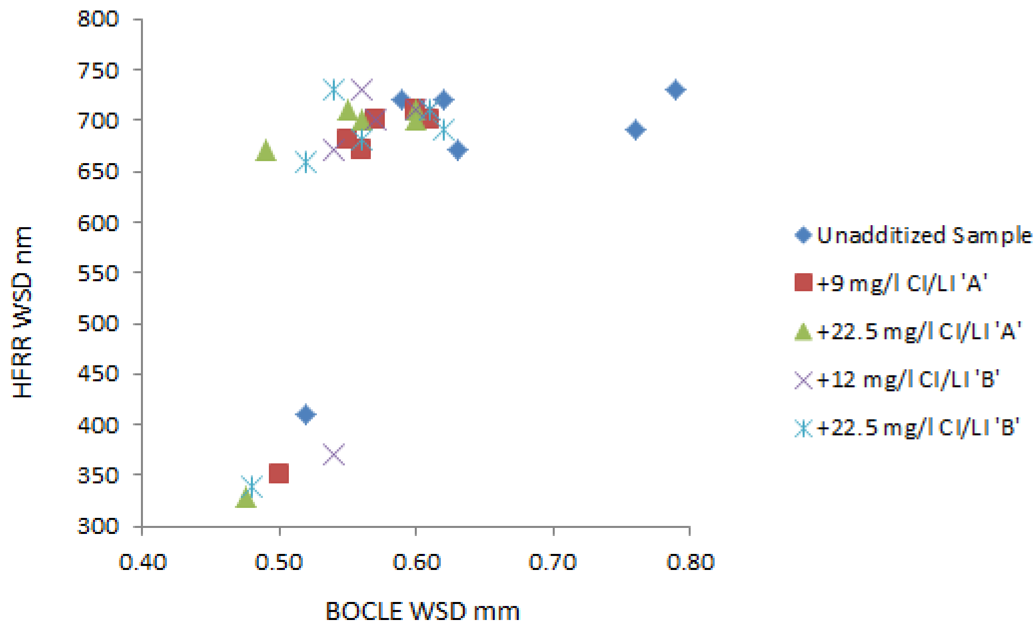

Figure 7: BOCLE wear scar diameter plotted against HFRR[34]

5.8.1 Modified HFRR: Hard-on-Hard Metallurgy

Hard (ball) on hard (disk) metallurgy HFRR tests have been carried out to simulate the metallurgy conditions in fuel pumps. Work was carried out by DERA for UK MoD on both diesel fuels[36] and jet fuels [37].

HFRR tests were carried out on diesel fuels using the test conditions as described in the CEC F-06-T-94 procedure[38] and as shown in the Table 2, except that hard disks were used instead of the soft ones. It was found that tests carried out at 200 g load as in the standard procedure did not show much discrimination between the fuels. Using Isopar M[39] as a standard poor lubricity fluid, loads in steps of 200 g were used up to 1000 g at which point severe wear was obtained; this weight also seemed to cause some distress to the rig. Therefore, a lower load of 800 g was selected for further tests.

[36] C.S. Matharu, “An Investigation of Tribological Tests for Diesel Fuels using Hard Metallurgy,” WIA 23/96/41.13.1/2 report for UK MoD.
[37] C.S. Matharu, “An Executive Summary of EMR Contract No NNR2/2054/1 - The Influence of Composition on the Lubrication Performance of Middle Distillate Fuels in Steel/Steel Contacts - Aviation Fuels,”WP 61/96/52.29/2.
[38] CEC F-06-T-94 went on to become ISO 12156 / IP450 which is almost identical to ASTM D6079.
[39] Isopar M Fluid is produced from petroleum-based raw materials which are treated with hydrogen in the presence of a catalyst to produce a low odor, low aromatic hydrocarbon solvent. The major components include normal alkanes, isoalkanes, and cycloalkanes.

Variable	Value
STROKE LENGTH	1 mm ±0.02 mm
LOAD	200 g
FREQUENCY	50 Hz ±1 Hz
TEMPERATURE	25 °C or 60 °C
DURATION	75 min ±0.5 min
FUEL VOLUME	1 ml ±0.2 ml
FUEL BATH SURFACE AREA	600 mm^2 ±100 mm^2

Table 2: CEC F-06-T-94 test conditions

Poor discrimination between fuels was observed. No correlation between wear scar and pump ratings was found at 25 °C, however, at 60 °C the trend was directionally correct. At 60 °C some fuels showed lower wear than at 25 °C; this was thought to be due to degradation of the fuel, visualised by a dark brown coating on the ball. Further tests were run under a different set of operating conditions, Table 3.

Variable	Value
STROKE LENGTH	1.41 mm
LOAD	10 N
FREQUENCY	71 Hz
TEMPERATURE	25 °C or 60 °C
DURATION	38 min
FUEL VOLUME	1 ml ±0.2 ml
FUEL BATH SURFACE AREA	600 mm^2 ±100 mm^2

Table 3: Improved HFRR test conditions

A good correlation was shown with the TAFLE scuffing load for eight jet fuels, Figure 8. It was concluded that this version of the HFRR method showed some promise as a potential test for both jet and diesel fuels. However, it should be noted that only a small number of samples were tested, no details on additive response and no statistical correlation data were given. Furthermore, the data were compared with TAFLE which may not be representative of aircraft fuel pump wear. Therefore there appears to be insufficient evidence to promote this modification of HFRR as a tool for jet fuel lubricity measurement.

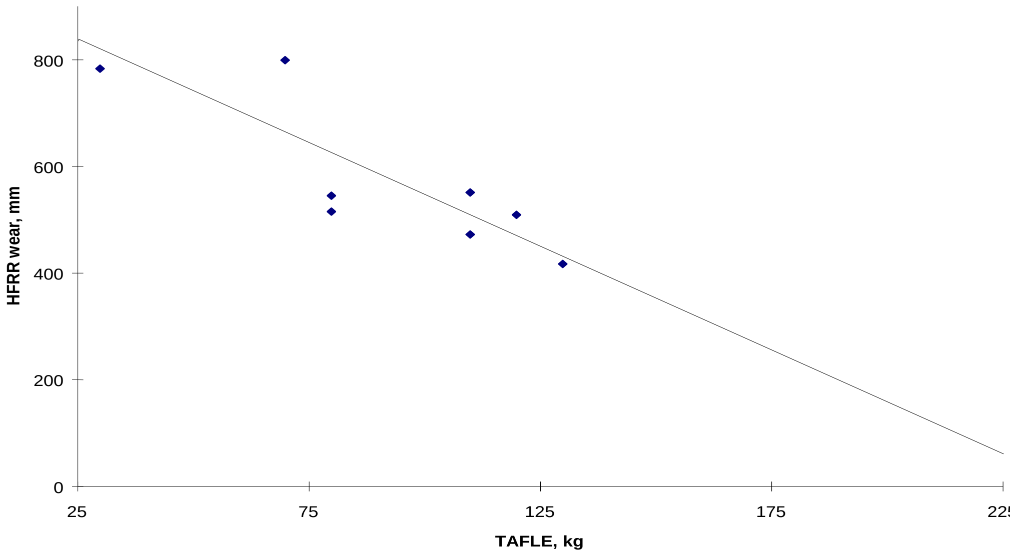

Figure 8: HFRR (TE77 71Hz) Wear vs TAFLE Scuffing Load for 8 AVTUR Samples[40]

5.8.2 Low Frequency Reciprocating Rig

Lacey[41] investigated why the HFRR test method conditions, despite a very low contact load, appear to be excessively severe, requiring too much additive to reduce wear. It was suggested that this observation may be due to the relatively high oscillating frequency used. The length of the stroke, and fuel quantity were also implicated.

Changes were implemented in a modified HFRR, known as the low frequency reciprocating rig (LFRR). The modifications were[42]:

1. Testing at 20 Hz (compared to 50 Hz)
2. 2 mm stroke length (compared to 1 mm)
3. Use of 20 ml fuel reservoir (compared to 2 ml)
4. Changes to wear scar boundary definition

In research investigating the use of jet fuels in diesel engines the LFRR reportedly showed an improved sensitivity to jet fuel lubricity additives[43]. Small amounts of jet fuel lubricity additives significantly decreased pump wear but the standard HFRR was not sensitive to the additives at low concentrations. Although the LFRR method appeared promising, when an ASTM method was drafted it did not receive support from industry as the research data did not indicate improved correlation to diesel pump

[40] C S Matharu, 'An Executive Summary of EMR Contract No NNR2/2054/1 - The Influence of Composition on the Lubrication Performance of Middle Distillate Fuels in Steel/Steel Contacts - Aviation Fuels', WP 61/96/52.29/2.
[41] Evaluation of the wear mechanisms present in the HFRR fuel lubricity test, P Lacey & B Shaver. Proceedings of the 2nd International Colloquium on Fuels, Esslinghen, Germany, January 1999.
[42] Email Matt Smeeth (PCS instruments) / Garry Rickard Nov 2012.
[43] Alternative Fuels: Assessment of Fischer-Tropsch Fuel for Military Use in 6.5L Diesel Engine. E A Frame et al, SAE 2004-01-2961, October 2004.

performance[44]. This could mean a modified LFRR may not be suitable for jet fuel lubricity measurement.

5.9 Ball on Three Disks (BOTD)

In 2005 the US Army published research detailing an evaluation of four laboratory test methods for lubricity to potentially replace a Military Rotary Fuel Injection Pump Rig Test which was used to evaluate JP-8/JP-5 for ground vehicle application [45]. This work built upon the earlier evaluation by Frame et al[31] referenced in Section 5.8. The methods featured were BOCLE, SBOCLE, HFRR and BOTD, the latter having been proposed as an ASTM method in 2000 ('P-TM'). The objective was to determine if the BOTD method was suitable for ground vehicle hardware and able to detect the benefits of CI/LI additive addition which was usually beyond HFRR. A Fischer-Tropsch test fuel was utilized, used pure and with 12 and 22.5 CI/LI additive. Results demonstrated both BOCLE and BOTD as sensitive to CI/LI additive concentration, with SLBOCLE and HFRR showing minimum response. Recommendations proposed some changes to the BOTD method to improve precision and possible benefits from using higher test temperatures, for example 50°C.

5.10 Fuel Pump Testing

There is limited information on correlation between BOCLE (ASTM D5001) and fuel pump wear available in the literature. Rolls-Royce and Lucas advised good correlation of BOCLE wear scar diameter to pump wear during testing in the 1980s, however, no data were reported[46].

In the early 1980's, tests were conducted at Southwest Research Institute to relate BOCLE wear scar with pump wear. Testing was conducted on two different main-engine pumps that were considered by the two pump manufacturers to have the highest speeds and loads at rated conditions of pumps being used at that time, and therefore would be the most sensitive to fuel lubricity. The pumps were tested at rated speed and load for 100 hours on JP-5's of varying BOCLE rating. The gears and bearings were replaced with new ones before each test. At the conclusion of each test, the gears were rated for the area percent of scuff, wear, erosion, frosting, and pitting. The dominant distress was scuff with frosting a distant 2^{nd}. The others were very minor if they were even present. A third pump type with an even lower speed and load at rated conditions was tested, but there was no scuff evident after 100 hours with a JP-5 with a BOCLE rating of 0.85 mm.

Figure 1 presents the results of this testing. Pump #1 was predicted to have the greater sensitivity to lubricity because the speed and loads are higher at rated conditions than for the 2^{nd} pump. The gear wear area on pump #2 exhibited essentially a linear relationship with the BOCLE rating. A linear relationship is more difficult to state for pump #1 since there was considerable scatter in the data at the higher BOCLE rating and no intermediate levels of lubricity. Nevertheless, it is important to note that at a BOCLE rating of about 0.67 to 0.68 mm, the scuff was essentially zero for both pump types. No testing was conducted with fuels of lower BOCLE rating.

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[44] Email communication between Steve Westbrook ofSwRI and Garry Rickard, November 2012.
[45] B. J. McKay, et al,, "Bench-Top Lubricity Evaluator Correlation with Military Rotary Fuel Injection Pump Test Rig," SAE Technical Report 2005-01-3899, Oct. 2005.
[46] Personal Communication from C. Moses to CRC July 29, 2014 extracted from unpublished U.S. Federal Government Research granted with permission of the U.S. Navy/NAPC

A second series of tests relating BOCLE wsd with gear wear was conducted using irradiated gears. The technique is known as Thin Layer Activation (TLA). During a test, the gear pump is monitored for radiation level. As the gears wear, the radiation level decreases at a rate faster than the normal decay rate. Figure 2 presents the results of this testing. Here, gear wear is in mils, i.e., 1/1000 inch. Again, the result is linear with BOCLE rating. Moreover, extrapolating the results to a condition of zero wear suggests a similar BOCLE level of about 0.69 mm.

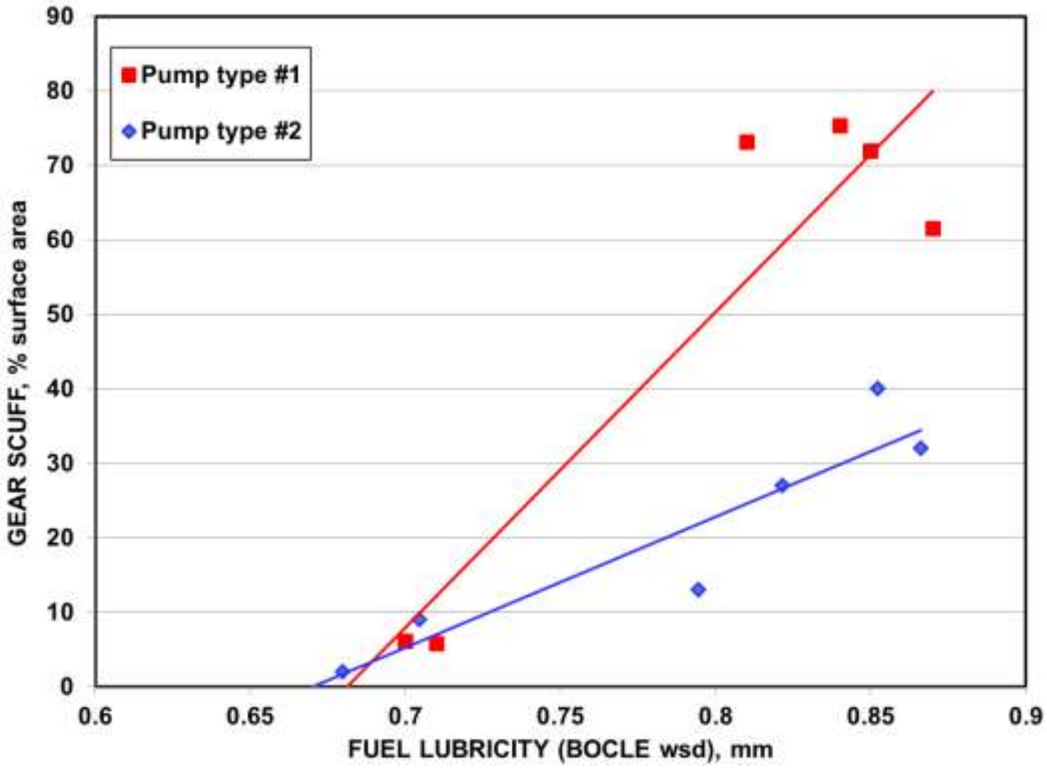

Figure 9. Effect of BOCLE Rating on Fuel Pump Gear Scuffing After 100 hours at Rated Speed and Load

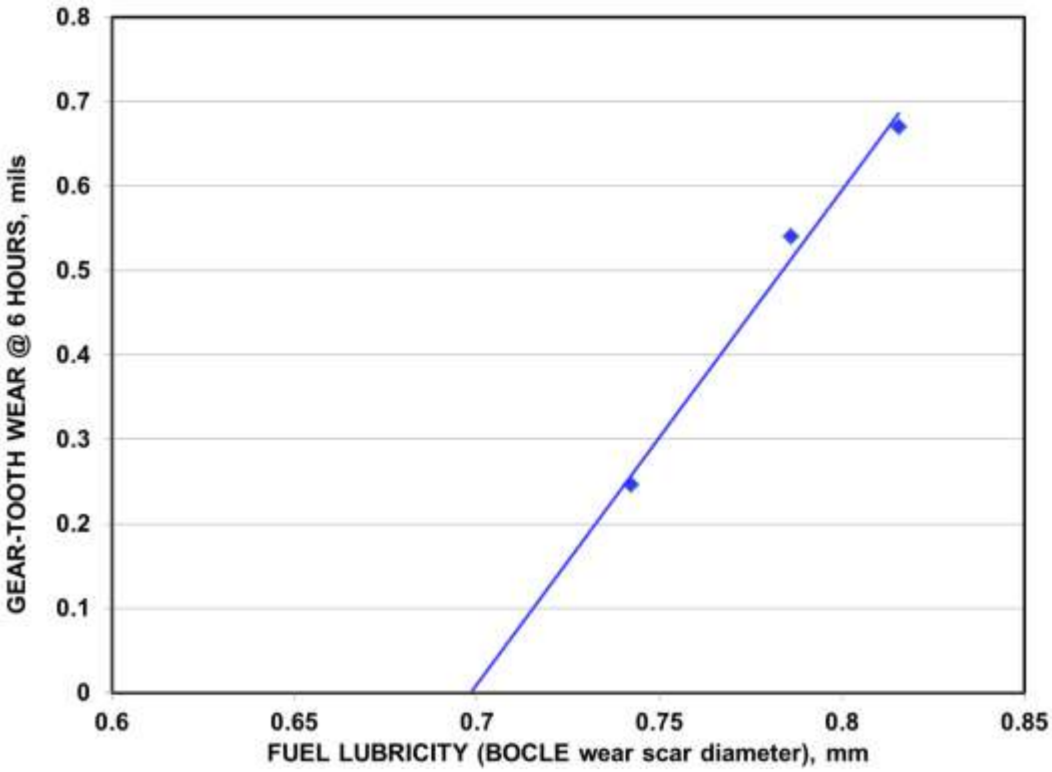

Figure 10. Effect of Fuel Lubricity (BOCLE) on Gear Wear After 6 Hours at Rated Speed and Load

A fuel pump test procedure is published by The Society of Automotive Engineers (SAE) as Aerospace Recommended Practice (ARP) 1797 'Aircraft and Aircraft Engine Fuel Pump Low Lubricity Fluid Endurance Test'. This document was originally issued in the late 1970s based on information available at that time. The companion document ARP 1794 described ball-on-cylinder measurement of lubricity, which owing to the different metallurgy used, gave significantly lower wear scar diameters than the later-developed ASTM D5001 BOCLE method. The test procedure used a fluid with a minimum wear scar diameter of 0.49 mm. Following the New Zealand lubricity problems in 1994-5, CRC and SAE worked together to modernise ARP 1797. The current ARP 1797 document, reaffirmed in December 2007, uses ASTM D5001 to define fuel test fluid lubricity. Defence Standard 91-91, the UK jet fuel specification, refers to ARP 1797 in its information statement on lubricity and states that future equipment proven against ARP 1797 procedure should not suffer lubricity related problems in use.

Following is a summary of ARP 1797:

> *This recommended practice defines procedures for testing aircraft engine fuel pumps for the purpose of determining their resistance to deterioration, while handling a specified standard low lubricity fluid. The procedure may also be used for other fuel system components, by testing in conjunction with the pump.*
>
> *The pump is operated at the speed, flow and discharge pressure required for normal engine maximum steady-state power at standard sea level*

conditions for 100 hours. The fluid used is MIL-PRF-7024 Type II[47] *with a BOCLE wear scar diameter between 0.85 and 0.96 mm, with a fluid temperature at pump inlet of 38°C to 41°C. Samples are taken at the beginning of the test, applicable test time commences with the taking of the first of two consecutive samples, extracted thirty minutes apart, that comply with the lubricity requirement. A clay filter may be used to filter all or any portion of the circulating fluid to maintain the required fluid condition.*

All test and inspection data is compiled in comparative tabulations to define performance changes and detail parts wear in relation to applicable new part requirements, service, and overhaul requirements.

After completion of the test, a report is prepared which documents the entire test and provides performance and wear data. Actual limits for wear performance are not defined, but may be agreed between the equipment manufacturer and the engine builder.

ARP 1797 is a recommended practice and it is not clear if all new pumps go through this process. At least one of the major engine manufacturers does not believe that this test protects their hardware sufficiently to allow them to operate on a continuous diet of fuel at 0.85 mm WSD for extended durations.

5.11 Section Summary

- Many mechanised test rigs for the determination of jet fuel lubricity have been developed over the past 40 years. Most do not simulate the most important type of wear exhibited in aircraft fuel systems. Data showing correlation of test results with pump wear are scarce.
- The BOCLE test in accordance with ASTM D5001 exhibits oxidative corrosion type wear to produce a measurable wear scar to quantify lubricity.
- There is limited information on correlation between BOCLE (ASTM D5001) and fuel pump wear available in the literature. Rolls-Royce and Lucas advised good correlation of BOCLE wear scar diameter to pump wear during testing in the 1980s, however, no data were reported. Unpublished U.S. federal government research carried out by Southwest Research Institute in the early 1980s appeared to show a linear relationship between BOCLE and scuffing wear with some pumps. Further evidence for the applicability of D5001 is its response to jet fuel lubricity improving additives, which are known to improve fuel lubricity.
- The Society of Automotive Engineers (SAE) publish Aerospace Recommended Practice (ARP) 1797 'Aircraft and Aircraft Engine Fuel Pump Low Lubricity Fluid Endurance Test'. This involves ensuring that a fuel pump can operate sufficiently for 100 hours with a low lubricity fluid (between 0.85 and 0.96 mm BOCLE in accordance with ASTM D5001). This is a recommended practice and it is not clear if all new pumps go through this process. At least one of the major engine manufacturers does not believe that the test protects their hardware sufficiently to allow them to operate on a continuous diet of fuel at 0.85 mm WSD for extended durations.

[47] Special run Stoddard solvent.

- HFRR is widely available in many fuel laboratories and there is some impetus to use this equipment for jet fuel testing. The HFRR in accordance with ASTM D6079 shows little/no correlation with BOCLE ASTM D5001 and no response to additive treatment of jet fuels. Various parameters within the HFRR are adjustable and it may be possible to modify the D6079 procedure to give a suitable test though nothing convincing has been developed yet.

6 Fuel Production Technology and Properties Affecting Lubricity

6.1 Influence of Fuel Chemistry on Lubricity

The relationship between lubricity and fuel composition has always been of great interest, as workers have tried to discover a chemical analysis for predicting a fuel's lubricity. This objective has never been wholly achieved. The vast number of trace chemicals that are present in petroleum distillate, and their low concentration levels, has made the identification of individual species responsible for lubricating properties very difficult. Furthermore, their influence on lubricity can be complicated by possible interactions between species. Nevertheless many studies have been carried out, and whilst it has not been possible to isolate all potential pro-lubricating compounds to be found in jet fuels, the broad categories have been identified. These are generally believed to be oxygenates covering a wide range of acidities, sulfur compounds and polynuclear aromatics. The identification of the classes of polar compounds that confer lubricity was partially determined by gas chromatography/mass spectrometry (GC/MS) analysis in work reported by Mills and Hadley[48] In hydrotreated fuels these were: carboxylic acids, alkyl phenols, methyl and di-methyl naphthols, and aromatic carbonyls. Merox treated fuels additionally contained benzothiophenes.

6.1.1 Aromatics

Polynuclear aromatics were one of the first classes of compounds identified in association with good lubricating performance. At one time total naphthalenes content was thought to have viability as a chemical test method to control fuel lubricity[49]. Because the ASTM D1840 method based on ultra-violet (UV) absorption was considered unreliable at low naphthalene contents, a more accurate GC based method was to be developed. Subsequent lubricity measurements on a wide variety of fuels showed that response to naphthalene in fact varied considerably between different base fuels. There appeared to be a naphthalene threshold above which all fuels had adequate lubricity, but the level was too high to be acceptable. It was concluded that it was not possible to define a lubricity specification by chemical analysis of naphthalenes.

Addition of a model compound such as 1-methyl naphthalene has produced mixed results for ball-on-cylinder wear. Beneficial effects on lubricity were noted for this compound in a paraffin base and in a base comprised of aliphatic solvent boiling in the kerosine range. But in clay-filtered JP-5 there was no improvement. A 3-ring aromatic (phenanthrene) additive was an even more effective anti-wear agent. However, 3-ring aromatics are not likely to occur in jet fuel in high enough concentration to affect lubricity.

6.1.2 Oxygen Containing Compounds

Long chain carboxylic acids are known to have excellent lubricating properties (di-linoleic acid type corrosion inhibitor/lubricity enhancers fall into this category). An early BOCLE

[48] B. Mills and J.W. Hadley, "The Influence of Composition on the Lubrication Performance of Middle Distillate Fuels in Steel/Steel Contacts," Liverpool John Moores University, Progress on MoD Contract NNR2/2054/1 to March 1995 – Supplement Sept 1995.

[49] J. Ogle, "Test Method for the Measurement of Turbine Fuel Lubricity," MOD(PE) Report on NATO/MAS Study 3665 F&L, June 1973.

study showed that addition of numerous different organic acids to clay-filtered JP-5 improved lubricity in all cases, even at low ppm dosage rates[50]. Lubricity continued to get better as acid concentration was increased. On the strength of these findings, an attempt was made to predict the lubricity of fuels from measurement of their acid number. However, lack of a strong correlation between acid number (by ASTM D3242) and WSD precluded this approach, probably due to the fact that trace species other than acids contributed to lubricity.

A study was carried out involving chemical analysis and lubricity measurements of a series of JP-5, Jet A and JP-4 fuel samples[51]. The analytical procedure was based on a method developed for determining the concentration of corrosion inhibitor additive in fuel. Direct correlation was shown between the amount of naturally occurring organic acids extracted from the fuels and their respective BOCLE wear scars. Combined gas chromatography/mass spectrometry (GC/MS) was then used to identify components in the acidic fractions. Specific alkanoic acids found ranged from heptanoic acid (C_7) to undecanoic acid (C_{11}). In most cases total acid concentration was of the order of a few parts per million. In addition to the acids, the fuel extracts contained some substituted alkyl phenols.

6.1.3 Sulfur Compounds

Corrosive mercaptans present in untreated kerosines are generally removed and the resulting sweetened fuels contain largely heterocyclic sulfur compounds and sulfides. These sulfur compounds of natural origin seem to have good anti-wear properties.

Early work by Esso on a pin-on-disc rig revealed a large difference in lubricity between a copper-sweetened and a severely hydrotreated fuel[52]. Comparing the compositions of these two fuels, the high lubricity sweetened fuel was found to contain a highly polar component, which was found to consist of the saturated heterocyclic sulfur compounds thiahydrindane and thiadecalin, together with a small proportion of benzothiophenes and naphthalenes.

Contrary results have emerged whenever the effects of model sulfur compounds have been evaluated. Most have been found to produce high wear under standard BOCLE conditions, although they have also provided excellent resistance to adhesive failure in the TAFLE[53]. For example, pro-wear properties in the BOCLE were displayed in tests on JP-5 fuel blends containing up to 2500 ppm of four different types of model sulfur compounds[54]. None of the substances improved lubricity. The conflicting behaviour of natural versus model sulfur compounds in a mild wear regime was not explained.

During and after the lubricity problems in New Zealand Shell collected data for the MoD on the lubricity of a range of jet fuels where sulfur content and refining process was known, Figure 11.

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[50] L. Grabel, "Lubricity Properties of High Temperature Jet Fuel," NAPTC-PE-112, Aug. 1977.
[51] B.H. Black, D.R. Hardy, and M.A. Wechter, "The Lubricity Properties of Jet Fuel as Measured by the Ball-on-Cylinder Lubricity Evaluator," Preprints of the Division of Fuel Chemistry, American Chemical Society, Vol. 35, No.2, pp547-570, Apr. 1990.
[52] R.A. Vere, "Lubricity of Aviation Turbine Fuels," SAE Technical Paper 690667, Oct. 1969.
[53] J.W. Hadley, "The Effect of Composition on the Boundary Lubrication of Aviation Turbine Fuels," Seminar on Tribology of Aviation Fuel Systems, Institute of Physics, London, Dec. 1989.
[54] Aviation Jet Fuel Seminar, CAA of New Zealand, Wellington, Sept. 1994.

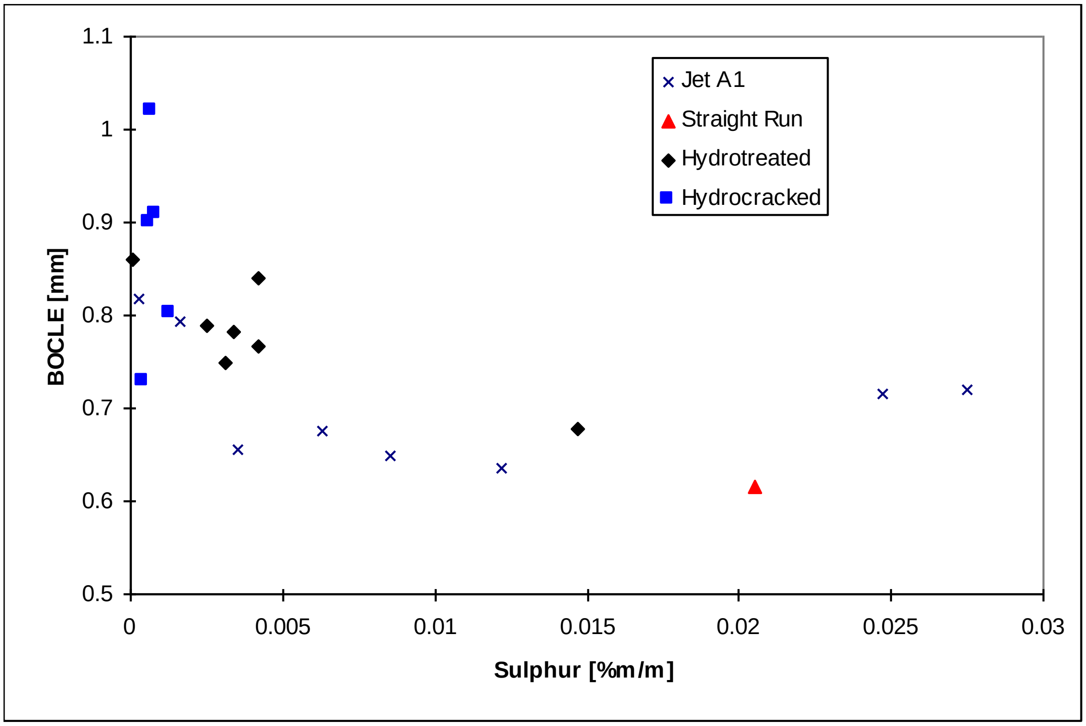

Figure 11: Data collected by Shell comparing fuel sulfur content with BOCLE wear scar diameter

Osman[55] reported the following relationship between sulfur content and BOCLE wear scar diameter, Figure 12.

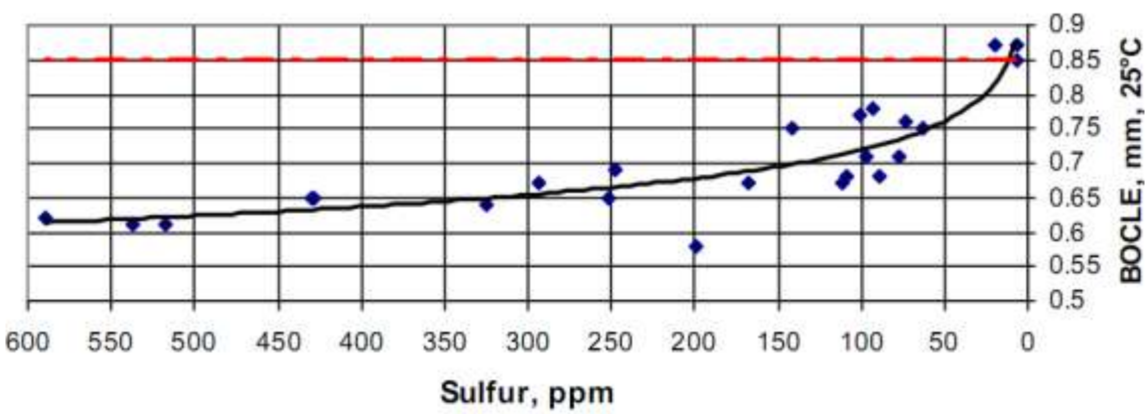

Figure 12: Jet fuel sulfur content plotted against fuel lubricity measured by BOCLE

[55] R. Osman, Flint Hills Resources, “Jet fuel lubricity, study of sulfur content effect and test method, BOCLE vs HFRR,”, CRC Aviation Committee Meeting, May 2012.

6.1.4 Surfactant Materials

Hardy[56] demonstrated that the detection of surfactant material in fuels correlates with lubricity. Surfactant materials are extracted and form an emulsion. The emulsion was measured on a small bench top turbidimeter with a range of 0.00 to 1100 nephelometric turbidity units and the logarithm of the turbidity reading used to compare fuels. The research was primarily to investigate the lubricity of diesel fuels; however, a number of measurements were also carried out on jet fuels and jet fuels with jet fuel type lubricity additives. The report concluded that the test was sensitive to both small changes in lubricity and to lubricity additives at low concentrations. Furthermore, it was reported that the test could easily be modified for field use. The test results suggested promise for jet fuel lubricity measurement or possibly as a screening test.

6.2 Effects of Different Refinery Processes

It is recognised that the lubricity properties of jet fuels result mainly from the presence of trace polar species (typically compounds containing oxygen and sulfur), whose concentration depends in the first instance on composition of the parent crude oil. Any changes in the concentration of these compounds brought about by refining processes used during manufacture are therefore likely to have an effect on the lubricity of the finished product. Refinery processes of concern here are secondary treatments that are used after distillation to modify or remove sulfur compounds. Kerosine distillates from most crude sources require such treatment in order to meet fuel specification limits for sulfur and mercaptan content, acidity and thermal stability. While the emphasis of the following discussion is placed upon the effect of these refinery processes on lubricity, the original link to crude oil source should not be forgotten. For example, anecdotal Italian evidence is that this can have a significant impact and the Industry may wish to consider crude oil type as part of further investigative work.

Currently the most widely used chemical sweetening process is Merox treatment - in which undesirable mercaptans are converted into stable disulfides by Merox catalyst and air at relatively low temperature and pressure. The overall level of sulfur in the fuel remains the same. Most of the natural lubricating agents present in untreated kerosine - trace compounds of sulfur and oxygen - are retained, with the result that lubricity of the finished product is normally not diminished. There are a number of other similar chemical sweetening process used and these are also not expected to produce poor lubricity fuels.

Hydrotreatment involves reacting the fuel with hydrogen over a catalyst at elevated temperature and pressure. Sulfur in mercaptan and other compounds is converted to hydrogen sulphide and subsequently removed. Overall sulfur level in the fuel is thereby reduced, as is the level of other heteroatomic compounds, such as those containing oxygen. These are precisely the trace compounds imparting good lubricity, and their removal will normally decrease the lubricity of the finished product. Just how low the fuel lubricity becomes depends on the severity of the hydrotreatment process used. Some jet fuel is produced by hydrocracking, a process carried out under more severe conditions than normal hydrotreatment. Hydrocracking will tend to remove even more of the trace components from a fuel and further reduce its lubricity.

[56] D. Hardy, "Development of a Fuel Lubricity Haze Test (FLHT) for Naval applications," Naval Research Laboratory, NRL/MR/6180-09-9177, March 2009.

Typical BOCLE fuel lubricities resulting from the different processes are[57]:

	WSD , mm
Merox sweetening	0.55 - 0.70
Hydrotreatment	0.75 - 0.85
Hydrocracking	0.85 - 1.05

Clark et al[58] showed that desulfurising a jet fuel from 2200 ppm to 10 ppm, by hydrotreatment, increased the BOCLE wear scar diameter from 0.51 mm to 0.79 mm.

Future environmental legislation may require the sulfur content of jet fuels to be reduced, requiring more extensive use of hydroprocessing to meet this demand. Hydrocracking is also expected to gain wider use as a conversion process. These may be long-term trends that could result in a gradual decrease or step changes in lubricity of jet fuel supplies. Further work might usefully be directed at investigating the link between hydrotreating process severity and fuel lubricity to seek an optimum for jet production.

A special case is the production of jet fuels from non-conventional sources as detailed in ASTM D7566 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons. Most jet fuels from non-conventional sources exhibit very low lubricity. For example Synthetic-paraffinic kerosine (SPK) in the boiling range for jet fuel made by a series of refining processes starting with hydrogen and carbon monoxide produced by gasification of organic components. Typical measured BOCLE values for SPK were found to be 0.85 - 1.04 mm. To control this property ASTM D7566 requires synthetic components to be blended with at least 50% conventional fuel and sets a BOCLE wear scar diameter of 0.85 mm maximum on the final blended product.

6.3 Clay Treatment

Trace compounds which contribute towards jet fuel lubricity can be removed during clay treatment. Clay treatment is widely used in the US and may cause significant changes to lubricity. The increase in wear scar diameter due to the loss of polar materials by clay filtration is illustrated in some examples in the Table 4[59]. In all cases the wear scar was increased by at least 40%.

[57] Aviation Jet Fuel Seminar, CAA of New Zealand, Wellington, Sept. 1994.
[58] Clark, et al ., “Jet fuel desulfurisation: an investigation into the impact of hydrotreatment on product quality,” , IASH conference, Sarasota, 2011.
[59] G. Datschefski, “History, development and the status of the ball-on-cylinder lubricity evaluator for aero gas turbine engines,” MoD Contract AE12a/193, March 1991.

Test Fuel	Cylinder Hardness, Rc	Wear Scar Diameter, mm	
		Untreated Fuel	Clay Treated Fuel
JP-5	20-22	0.34	0.56
Shale JP-5	20-22	0.49	0.66
ERBS fuel	20-22	0.34	0.50
Coker Distillate	20-22	0.55	1.08
Jet A-1	58-62	0.60	0.85
Jet A	58-62	0.56	0.82
JP-4	58-62	0.56	0.81

Table 4: Changes in lubricity following clay treatment

The data in the table above was carried out with BOCLE [60] test conditions of 1000 g load at 10% RH purge air. The test conditions are not identical to the current standard D5001. Nevertheless, the data indicates significant reduction in lubricity due to clay filtration. There appears to be minimal data in the public domain that shows how clay treatment within the distribution system affects jet fuel lubricity. It would be useful to generate more data to establish the impact.

It is a common industry practice to use clay filtration to generate hard lubricity fuels for use in testing. A number of hardware manufacturers routinely filter the test fluid during endurance testing to maintain the necessary lack of lubricity for the duration of the test.

6.4 Effect of Blending Fuels of Different Lubricities

BP carried out some investigations[61] on the effect of blending hydrocracked kerosine (which generally has a low lubricity), and straight run kerosine (which generally has a high lubricity). It was observed that adding even a small percentage of straight-run kerosine to hydrocracked kerosine significantly reduced the BOCLE wear scar diameter. The results can be seen in Figures 13 and 14.

[60] It should be noted that the specifications of the test cylinder used in the BOCLE were changed at least five times between 1968 and 1990; therefore comparison of results during this period is not always valid.

[61] G. Rickard and G. Datschefski, " Lubricity Review," Technical report to UK MoD DERA/MSS1/CR990253, Jan. 1999.

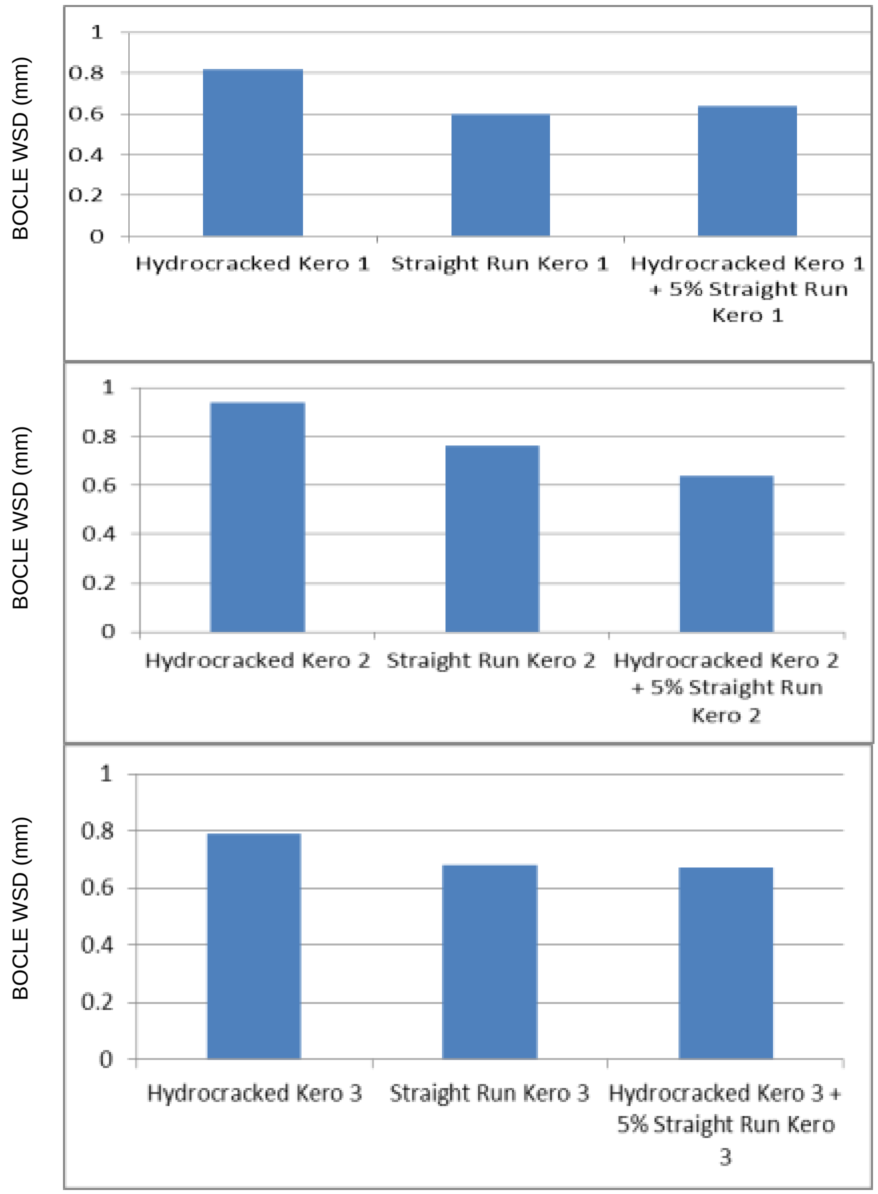

Figure 13: The effect of blending hydrocracked kero with straight run fuel.

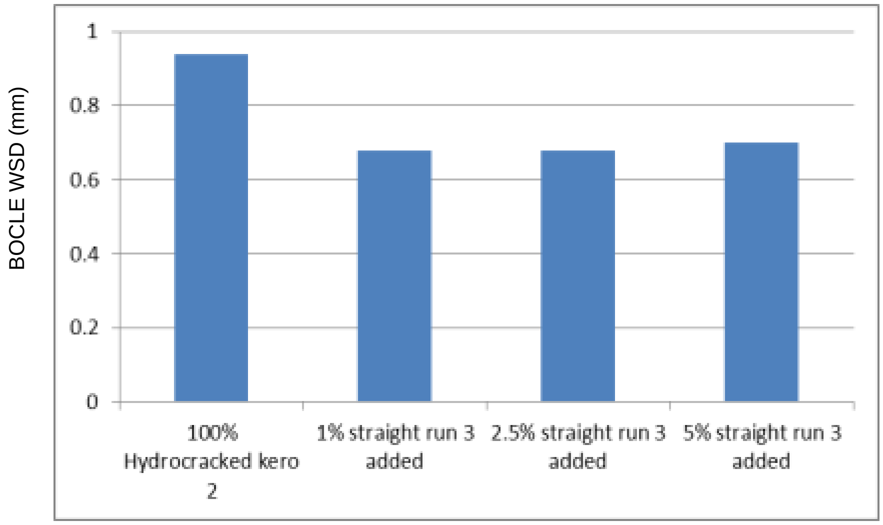

Figure 14: The effect of blending different quantities of straight run jet fuel into hydrocracked on BOCLE results

6.5 Impact of Co-Mingling and Contamination During Distribution

During distribution, aviation fuels can become co-mingled with other aviation fuels. It is shown in the Table above that mixing just 1% of high lubricity material into a low lubricity fuel can substantially improve its lubricity (as measured by BOCLE). Since trace amounts of polar material can significantly improve lubricity it is unlikely that co-mingling (and possibly contamination) will cause a decrease in the lubricity of aviation fuel. Therefore the distribution system may improve the lubricity of aviation fuel delivered to aircraft compared to the fuel lubricity at the refinery.

6.6 Trends and Changes in Refining Practice

Although total fuel sulfur content is not directly related to lubricity, low sulfur is a likely indicator of refinery processes which remove the trace materials that impart lubricity. Therefore, a study of trends in sulfur content may indicate the probability of a trend in fuel lubricity. The use of refining processes for jet fuel which reduce sulfur contents to very low levels could be increasing and may increase further in the future for a number of reasons.

- An increase in heavier crudes may be leading to more hydrocracked and heavily hydrotreated jet fuel.
- The use of hydrotreatment for other fuels which require very low sulfur contents may have an effect on jet fuel sulfur contents.
- Future legislation may change sulfur content of jet fuel.

6.6.1 Fuel Sulfur Content Trends

A study of jet fuel sulfur levels, at point of production, has been carried out by Taylor [62] on behalf of the CRC. This reported that the overall US region sulfur content dropped

[62] W.F. Taylor, "Update of the Survey of Sulfur Levels in Commercial Jet Fuel," CRC Report AV-1-10, Sept. 2012.

from 704 ppm in 2005 to 544 ppm in 2010. However, it can be seen from Figure 15 below that there is some fluctuation in the data and a significant downward trend is not certain.

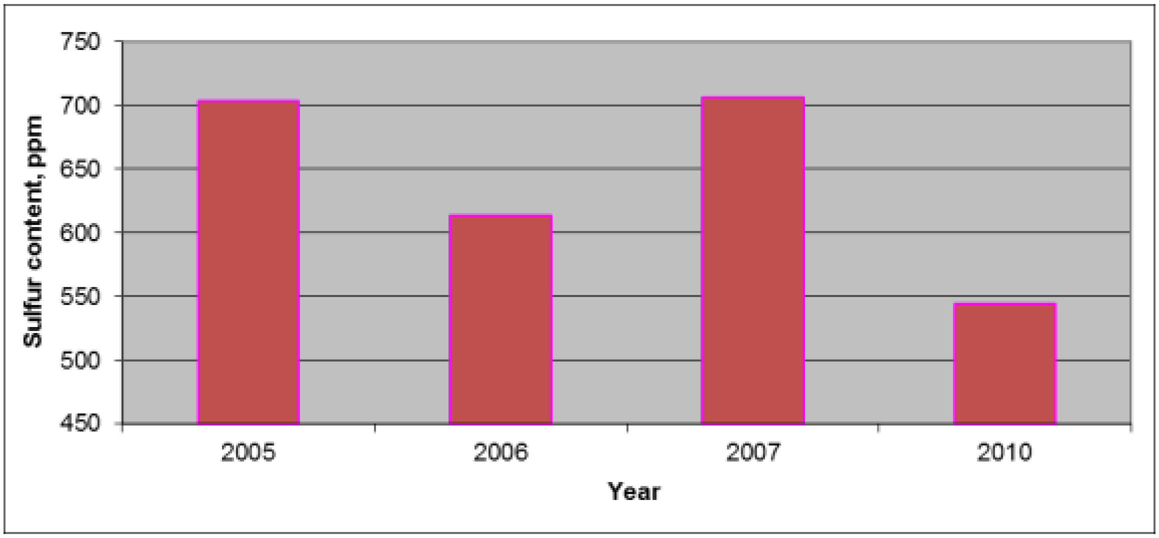

Figure 15: Average September to December jet fuel sulfur content for US for 2007-2010.

Perhaps more important than the mean sulfur content is the quantity of ultra-low sulfur (<15 ppm) jet fuel being produced, which is likely to exhibit poor lubricity. The survey showed that the percentage of ultra-low sulfur jet fuel increased from 3.4% in 2005 to 8.0% in 2010 as shown in Figure 16.

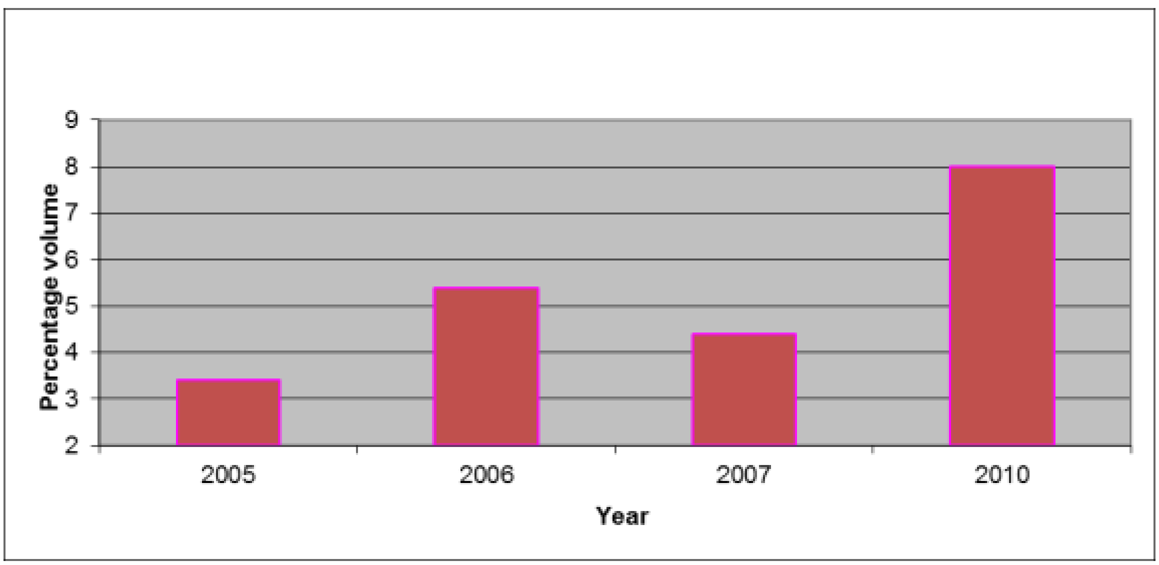

Figure 16: Ultra low sulfur (<15 ppm) fuel production in US 2005-2010

In Europe there appears to be a much higher percentage of jet fuel which is ultra-low sulfur. Taylor reported 5.2% volume in 2005 rising to 15.5% in 2010.

The Defense Logistics Agency Energy (DLA Energy) produces the Petroleum Quality Information System Fuels Data (PQIS) on an annual basis. The 2013 PQIS report[63] gave details of sulfur contents of 107 samples of Jet A-1, representing 361 million US gallons, showing a weighted mean of 0.138% mass and 1180 samples of JP-8, representing 1096 million US gallons, showing a weighted mean of 0.076% mass. Figures 17 and 18 showing sulfur content of these two products are given below. No long term trends over time are evident.

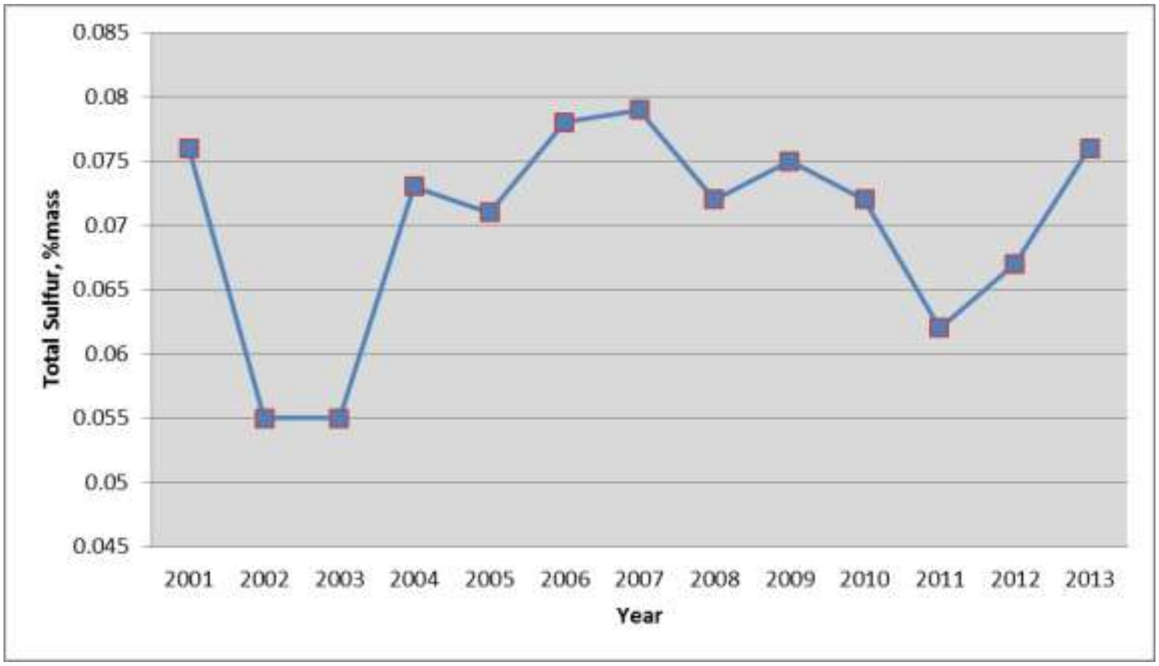

Figure 17: PQIS data for US JP-8 sulfur content, 2001-2013

[63] 2013 PQIS Report. P Serino, Defense Energy Support Center.

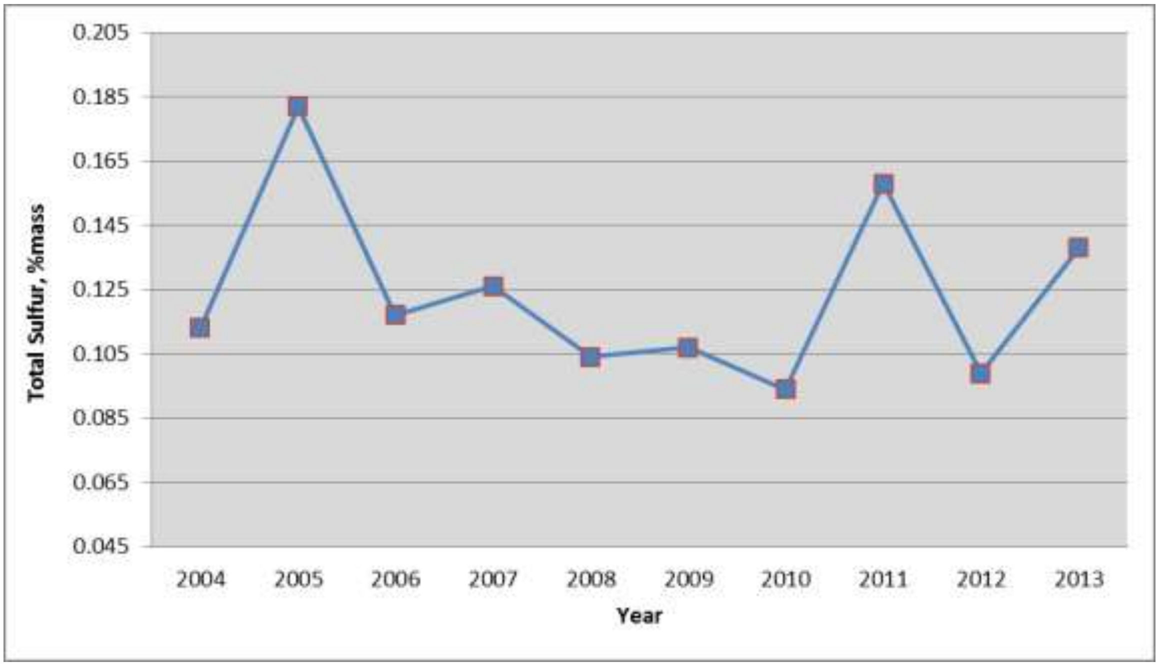

Figure 18: PQIS data for US Jet A-1 sulfur content, 2004-2011

Annual surveys of fuel manufactured or imported into the UK were reported annually until 2008[64]. The trend in sulfur content is shown in the Figure 19 below. Although a trend is difficult to see, the last few years showed higher results than observed in the previous 15 years.

[64] G.K. Rickard, "The Quality of Aviation Fuel Available in the United Kingdom Annual Survey 2008," QinetiQ/09/01120, Dec.2009.

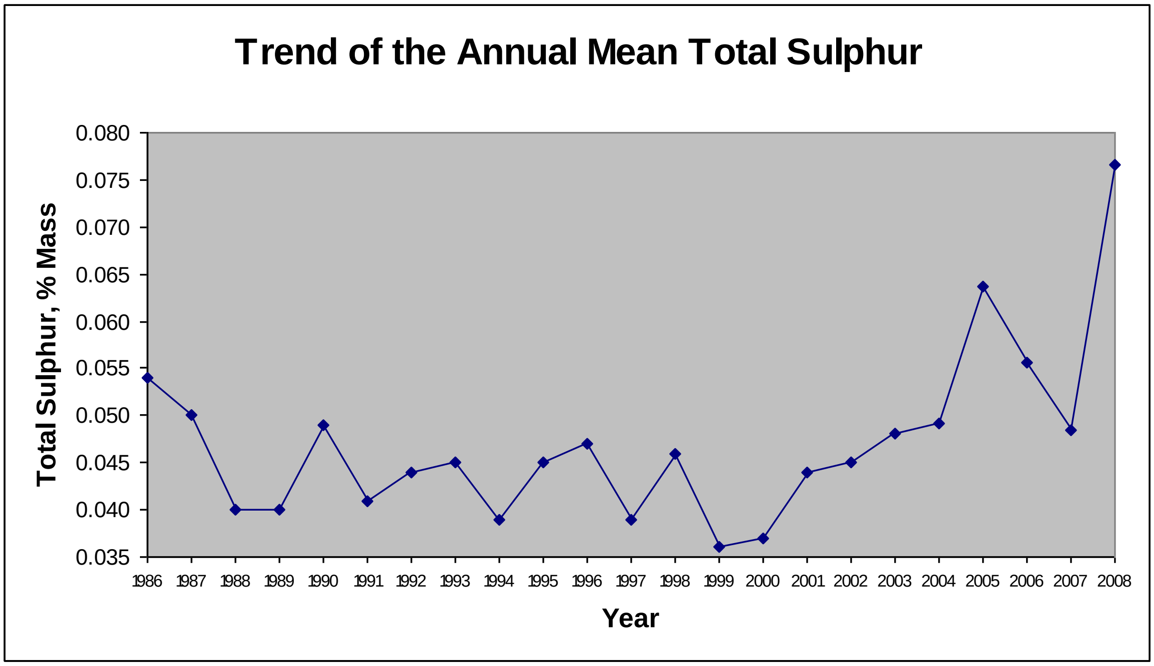

Figure 19: Annual mean sulfur content for UK jet fuel, 1986-2008

Perhaps of more interest than the weighted mean results is to look at the trends in more detail. The authors believe that there has been an increased use of heavier, higher sulfur crudes which could cause a change in both the quantity of very high sulfur jet fuel (due to blending of high sulfur feed stocks) and very low sulfur jet fuel (due to severe hydrotreatment of heavy crudes). This was investigated using the UK survey data. It can be seen that the percentage of high sulfur jet fuel (>0.2% mass) increased in recent years as shown in Figure 20. However, it was not possible to investigate, with any accuracy, the changes in low sulfur jet fuels. This is because there are a number of different methods used to measure sulfur content in jet fuel with different detection limits and reporting requirements. Commonly, sulfur levels of "<0.01 % mass" (100 ppm) are reported. Therefore, if there was significant change in the spread of fuels produced in the 0 and 100 ppm region (which could be significant with respect to lubricity), this would not necessarily be obvious from the data collected. So, in conclusion, the data from the UK survey indicates an increase in the amount of very high sulfur batches but it is not possible to investigate if there is an increase in very low sulfur fuels due to the reporting and test methods used.

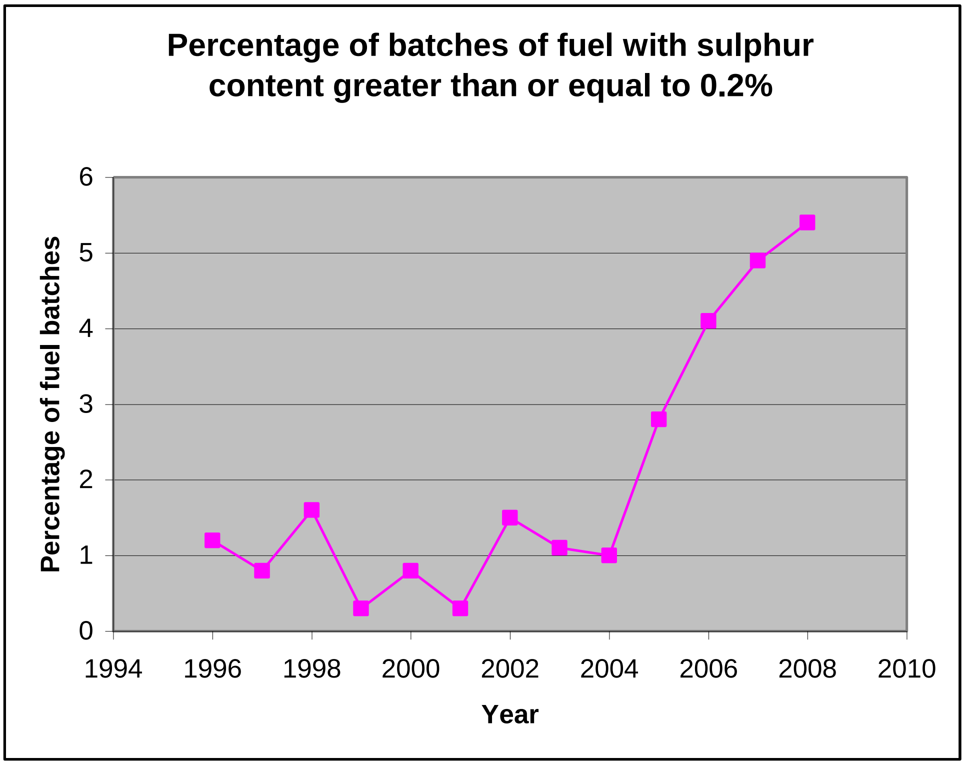

Figure 20: Percentage of batches of UK jet fuel with sulfur content greater than 0.2%[65]

6.7 Legislation

The sulfur levels in jet fuel may be decreased not just by natural change due to the market and choice of crude materials but also due to legislation. An environmental cost-benefit analysis of ultra-low sulfur jet fuel (15 ppm max) was carried out[66] on behalf of the US Federal Aviation Administration Office of Environment and Energy. This project reported aircraft emissions can reduce air quality, leading to adverse health impacts. To obtain ultra-low sulfur fuel, environmental costs would include an increase in average climate warming caused by aviation by 1-8% because of the increased energy use to produce the fuel at the refinery. However, the use of this fuel is likely to prevent 1000-4000 premature mortalities per year if implemented globally. The report notes that the cost-benefit reported has relatively high levels of uncertainty and the methods used are subject to debate. A similar study has also been conducted by QinetiQ on behalf of EASA[67] . It is not clear at this time if these reports will lead to legislation to reduce sulfur in jet fuel either world-wide or in the US/Europe. If sulfur in jet fuel were to be limited to 15 ppm, the effect on lubricity would likely be significant and the use of lubricity improving additives would probably be required. Any changes to reduce levels to a 15 ppm sulfur specification limit would require a long lead time to allow for refinery and distribution changes[68].

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[65] Data extracted from various UK MoD funded jet fuel quality surveys 1994-2008.
[66] Barrett, et al., "Environmental cost-benefit analysis of ultra-low sulfur jet fuel," PARTNER 27 final report, De. 2011.
[67] "Reduction of sulphur limits in aviation fuel standards," QinetiQ/09/01835, Jan. 2010.
[68] "Sulfur in Jet Fuel Workshop." QinetiQ Farnborough, September 2002.

6.8 Section Summary

- Trace species in jet fuel, such as naphthalene, sulfur and oxygen compounds, can have a major influence on fuel lubricity.
- Sulfur content is not directly indicative of lubricity for a given fuel. Poor lubricity is generally linked to the removal of polar compounds during hydrotreatment, especially severe hydrotreatment. A very low sulfur fuel is, however, likely to exhibit poor lubricity because of the coincidental removal of polar species during the sulfur removal process.
- Fuels from non-conventional sources, essentially synthesised hydrocarbons, are generally without polar materials and are therefore likely to exhibit poor lubricity.
- Blending small percentages of straight run or Merox type fuels significantly increases a fuel's lubricity. Addition of 5% of such fuel to a low lubricity fuel typically improves the lubricity significantly.
- During distribution any co-mingling is likely to improve fuel lubricity. Conversely, clay treatment in the distribution system is likely to remove trace polar materials and could significantly reduce fuel lubricity. Additional data to better understand the impact of clay treatment would be advantageous.
- Market survey data provided by Taylor suggests that the quantity of ultra-low sulfur jet fuel in the US and the EU is rising. Therefore, there is a likelihood of an increase in low lubricity fuel.
- It is not clear if legislation to reduce sulfur content in jet fuel is likely, but, if it occurs and sulfur levels in fuel are 15 ppm or less, low lubricity jet fuel is likely to be prevalent.

7 Lubricity Data on Production Fuels

During the past 30 years a number of different surveys have attempted to establish jet fuel lubricity levels at refineries or in the distribution system downstream to the aircraft for both civil and military operators as a result of fears that fuel lubricity may be causing or could cause operational issues. The results of the sampling surveys are described below.

7.1 Rolls-Royce/Lucas Survey

In the mid-1980s an airline experienced service problems with premature wear failures of the gear pump in Rolls-Royce RB-211 engines. Low lubricity fuel supplies were a suspected cause, centred around the Middle East region where jet fuel production was known to be hydrotreated and in some cases hydrocracked. Rolls-Royce consequently set up a fuel sampling exercise with the objective of identifying the possible sources of low lubricity fuel[69]. Samples from aircraft, airports and refineries were taken, concentrating initially on the Middle East but then extending to other locations around the world for purposes of comparison. Lubricity of all samples was measured in the Lucas Aerospace laboratory, which, at that time, operated one of the few available BOCLE machines in the UK. Results were reported by Rolls-Royce and Lucas and showed good correlation with service experience[70]. Middle East sourced fuels showed markedly higher average WSDs than European and North American sourced fuels. The results are summarized in Tables 5 and 6 below. It is believed that this is part of the data that led Rolls Royce to support the Defence Standard 91-91 lubricity requirement (Section 8).

[69] Report of MOD(PE) Aviation Fuel Committee Lubricity Steering Group for period March 1985 to October 1986.

[70] G. Rickard and G. Datschefski, "Lubricity Review," Technical report to UK MoD DERA/MSS1/CR990253, Jan. 1999.

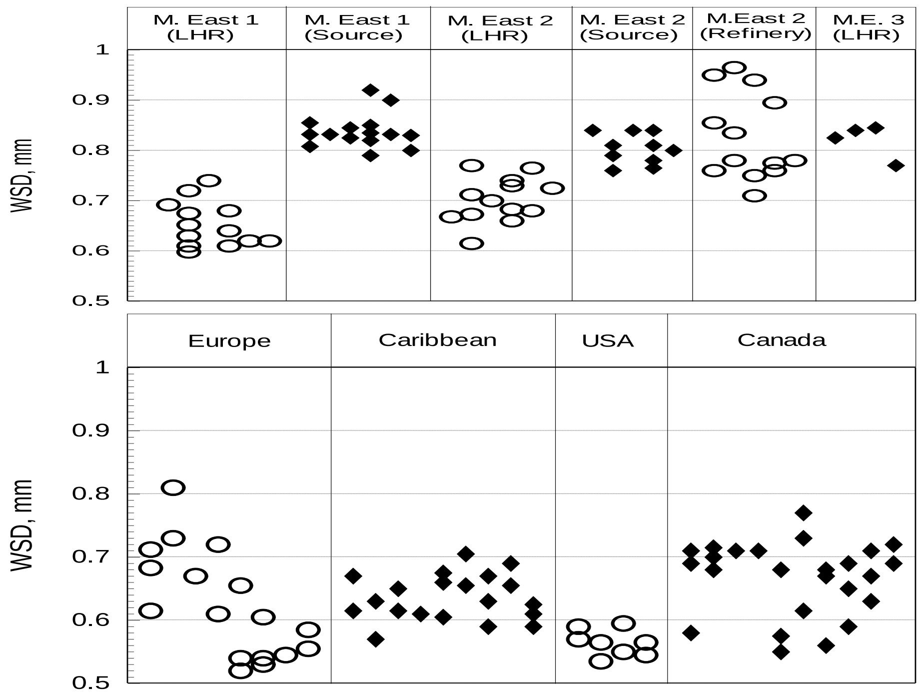

Table 5: BOCLE Data: Results of Rolls-Royce Survey (1984-1986)

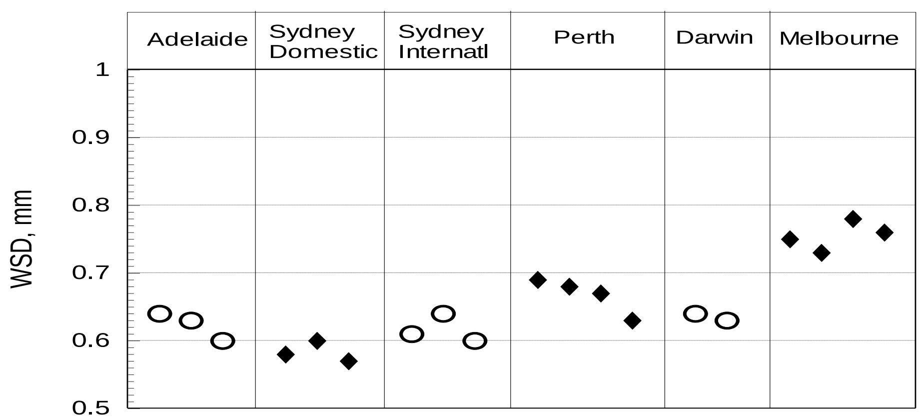

Table 6: BOCLE Data: Rolls-Royce Australian Fuel Samples collected Aug-Nov 1986

7.2 British Airways Survey

A fuel monitoring exercise was carried out by British Airways in 1990[71] to highlight differences in lubricities of fuel supplies from various locations. Results of the world-wide survey are given in the table below and show that a refinery in Australia (Australia – Refinery B) was at the time of test producing fuel having the highest WSD. Istanbul

[71] Report of MOD(PE) Aviation Fuel Committee Lubricity Steering Group for period Mar. 1985 to Oct. 1985.

airport supplies also produced relatively poor lubricity fuel. The results are summarised in Table 7 below.

Location	BOCLE WSD (mm)
Refineries:	
Australia – Refinery A	0.78 / 0.80
Australia – Refinery B	0.86 / 0.86
USA – Refinery A	0.75 / 0.75
USA – Refinery B	0.64 / 0.65
United Kingdom	0.62 / 0.63
Airports & Depots:	
Turkey	0.80 / 0.80
Cyprus	0.68 / 0.70
UK – Location A	0.58 / 0.57
UK – Location B	0.58 / 0.60
Australia – Location A	0.77 / 0.80
Australia – Location B	0.61 / 0.61
Airports:	
Bahamas	0.75
Bahrain	0.74
USA	0.58
Singapore	0.65
UK	0.56 / 0.58

Table 7: BA world-wide survey of BOCLE data

7.3 World Fuel Sampling Program

A collaborative study to look at properties of jet fuel from across the world was supported by a consortium of GE, Boeing, Goodrich, Chevron and USAF[72]. 57 samples were drawn from 18 countries. All the fuels had lubricities below the UK Defence Standard 91-91 maximum of 0.85 mm WSD by BOCLE test. No correlation was established between sulfur content and lubricity although the report's authors suggested that fuels below 100 ppm sulfur had higher WSDs, Figures 21 and 22.

[72] "World Fuel Sampling Program," CRC Report No. 647, June 2006.

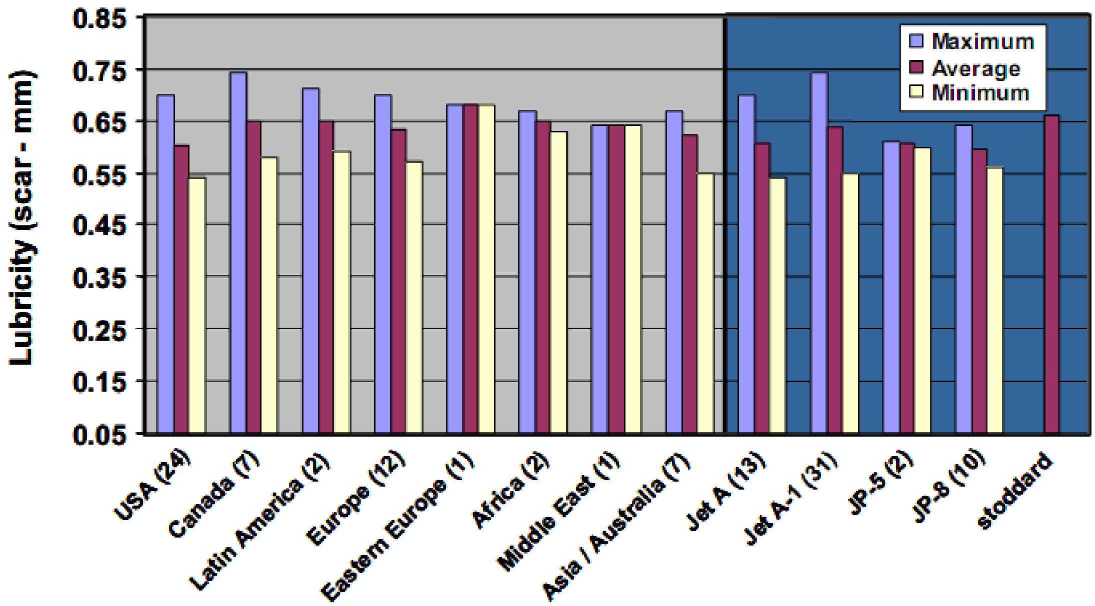

Figure 21: Lubricity data from World Fuel Sampling Program

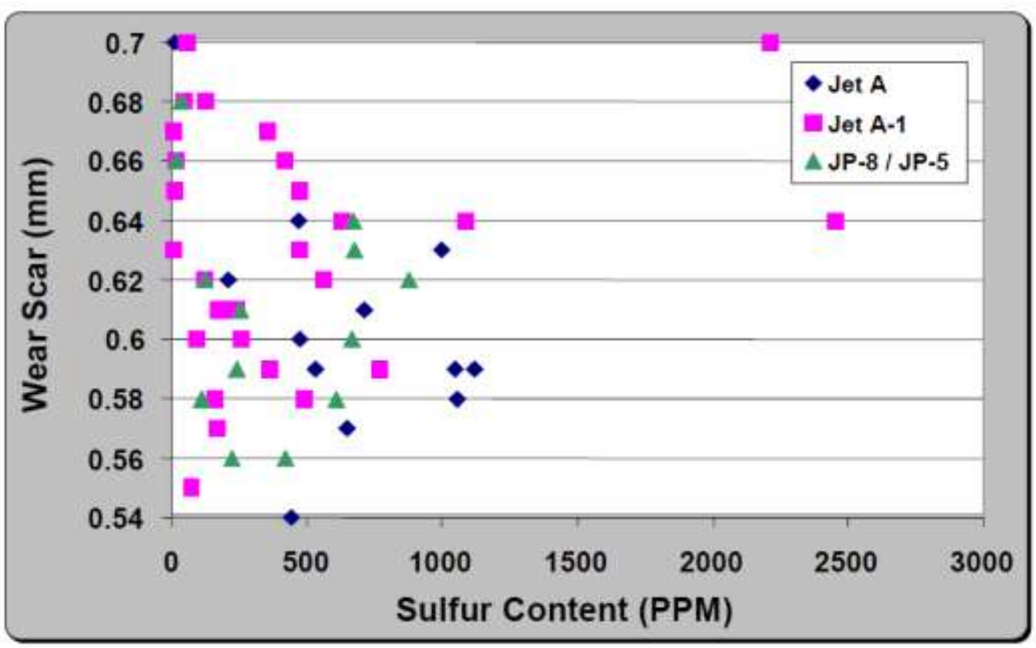

Figure 22: Lubricity compared with sulfur content from the World Fuel Sampling Program

7.4 USAF Survey of World-Wide Into-Plane Samples

The United States Air Force (USAF) conducted a testing program designed to assess the quality of aviation turbine fuel delivered to military aircraft at commercial airports [73]. Samples from 493 locations world-wide were taken quarterly by the contractor and tested in a government laboratory. Since early 1996 BOCLE (ASTM D5001) tests have been carried out on these samples where equipment is available.

For the USAF survey a pass/fail criteria of 0.65 mm maximum WSD was set. This limit was used because the military normally inject lubricity improving additives, the minimum concentration allowed being based on a standard low lubricity fluid that gives a BOCLE wear scar diameter of 0.65 mm.

The USAF reported that in 1996, of the 633 samples tested 32% failed the BOCLE WSD ≤0.65 mm criteria and in 1997, 31% out of 1213 samples failed. These tests were carried out on Jet A and Jet A-1 without lubricity additive. The distribution of BOCLE results from February 1996 to August 1997 is shown in Figure 23.

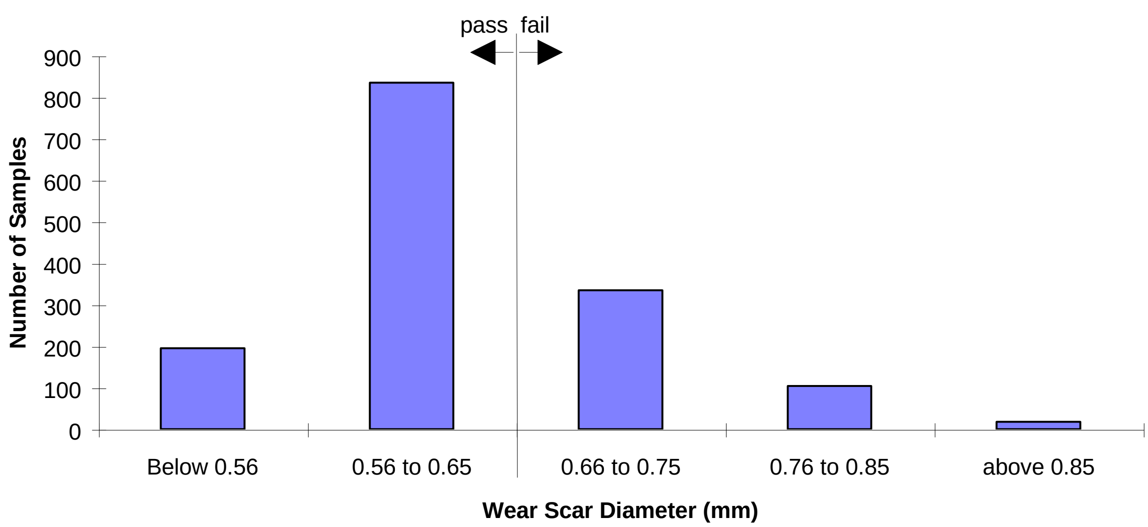

Figure 23: Distribution of "into plane" BOCLE results with USAF 0.65 mm Pass/Fail Criteria

Figure 24 shows how BOCLE wear scar diameter varied for fuels throughout the world.

[73] N. Makris, "'In-to-Plane contract testing," presentation to Aviation Fuel Lubricity Group of the Coordinating Research Council, June 1997.

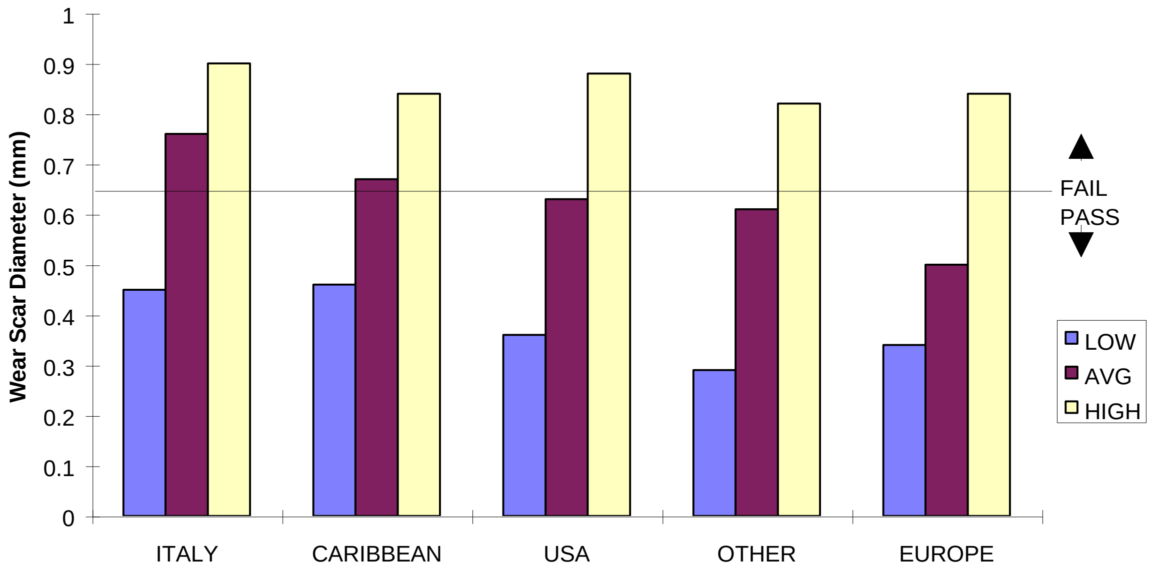

Figure 24: World distribution of BOCLE results with USAF 0.65 mm Pass/Fail Criteria

In conclusion, the data indicates a high incidence of BOCLE failures throughout the world, when using the USAF BOCLE pass/fail criteria of 0.65 mm WSD. This is much lower than the current Defence Standard 91-91 limit of 0.85 mm.

7.5 Further USAF Into-Plane Data

The requirement to measure lubricity of certain fuels was introduced into the UK Defence Standard 91-91 in December 2000[74]. Data from the USAF into-plane survey from regions around the world, but not including the US, was analysed to determine whether there was any discernible change in fuel quality[75]: BOCLE results were sorted into two groups: before 1st December 2000; and after 1st December 2000. The data set included 786 samples before the specification change and 541 after the change. The mean BOCLE wear scar diameter was the same (0.66 mm) for both groups. The percentage of BOCLE results greater than 0.85 mm was 3.06% before 1st December 2000 and 1.85% after. The data can be seen in graphical form in the Figure 25.

[74] Once lubricity was included in the Defence Standard it was also required in “Checklist” which, outside the US, is the de facto international Jet A-1 specification in many regions. www.jigonline.com/wp-content/uploads/2012/05/Bulletin-51-AFQRJOS-Issue-26-May-2012.pdf

[75] Rickard, G, “Evaluation of lubricity requirement in Defence Standard 91-91”, reported to AFC ExCo 2003.

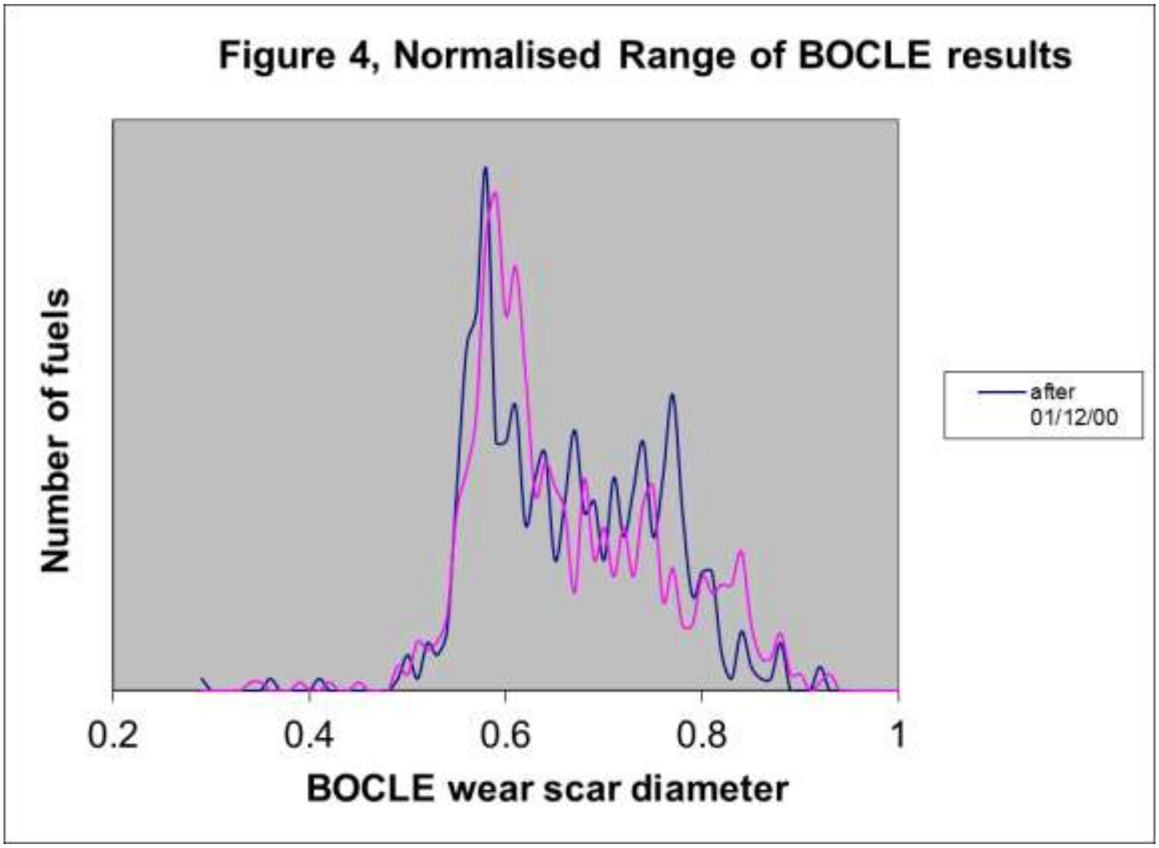

Figure 25: Data showing possible change in fuel lubricity following specification change[76]

The percentage of BOCLE results greater than 0.85 mm before and after the specification change suggests that some of the lowest lubricity fuels were removed from the jet fuel pool. (This also may be due to fewer fuel pickups in the areas where low lubricity fuels were supplied - which cannot be determined from the data - however the large data set suggested the change may have been significant). The observation that 1.85% of into-plane results still failed the specification was unexpected. This might be due to:

- The precision of the BOCLE method, repeatability 0.08 mm / reproducibility 0.12 mm at 0.85 mm WSD.
- Changes in the composition of the fuel over time due to a particular crude oil selection and/or manufacturing process.

The most recent data from the USAF[77] on into-plane surveys gives information on current lubricity values at delivery to aircraft. As can be seen in Figure 26 only one sample out of 3735 exceeded 0.85 mm BOCLE wear scar diameter, which occurred in 2007.

[76] The data has been normalised so that the areas under the curves are the same for each sample set.
[77] Communications between G Rickard and C McCormick (of Defense Logistics Agency, Sept. 2012.

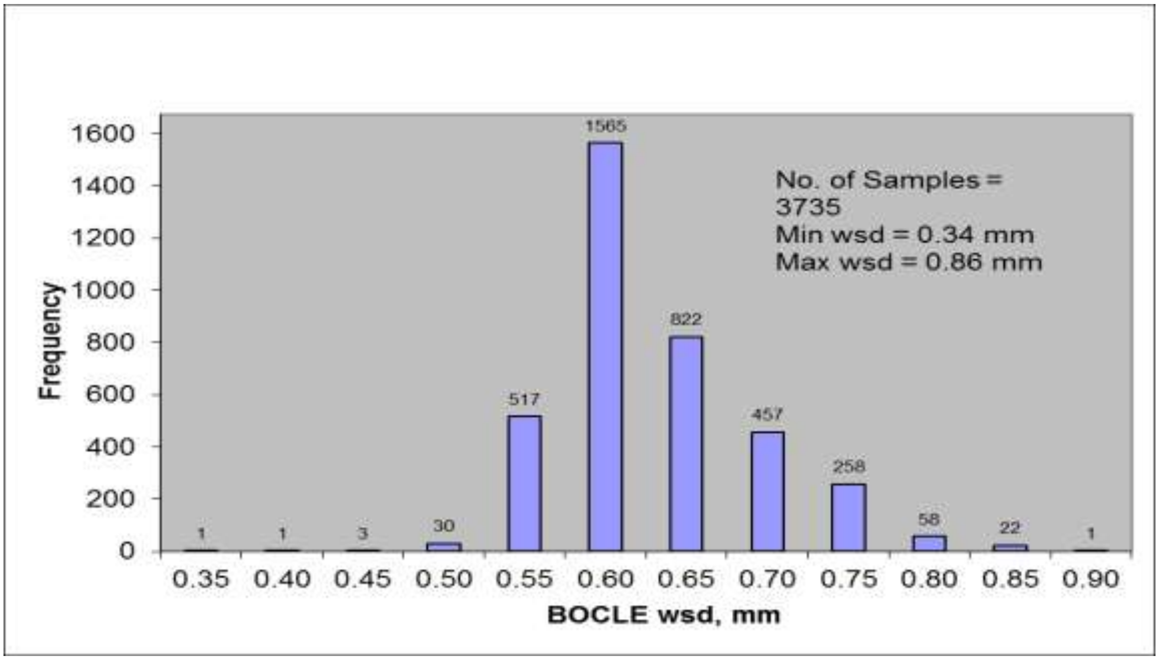

Figure 26: Lubricity data from 2007-2011 drawn from the USAF into plane survey[78]

The mean wear scar diameter by year is shown in Figure 27 below.

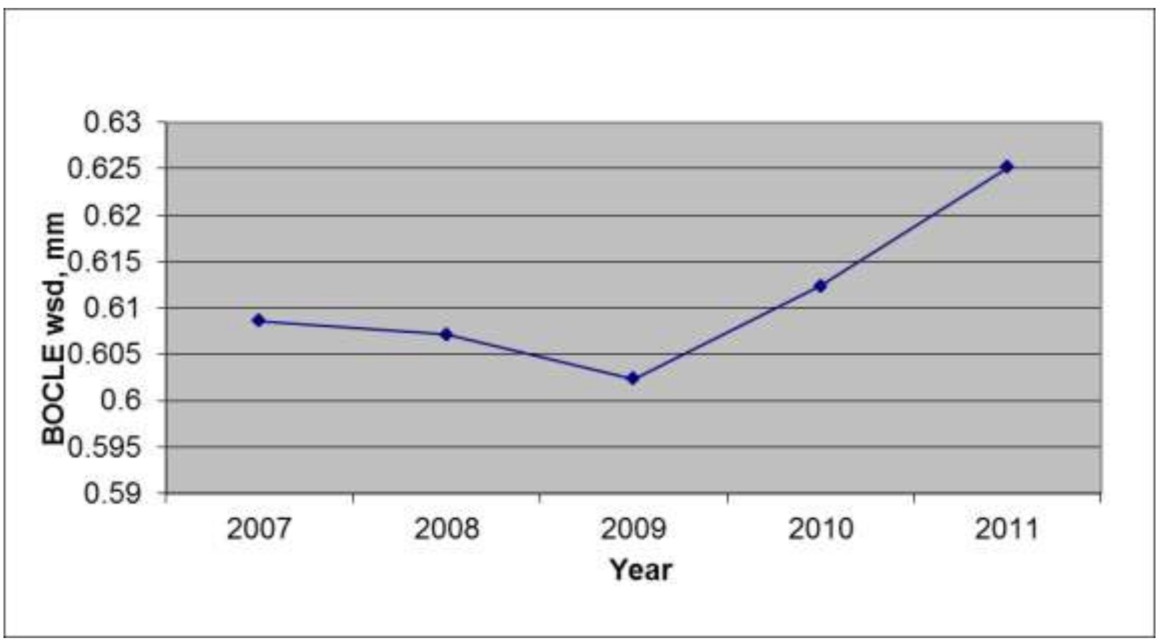

Figure 27: Data from USAF into plane survey showing mean lubricity for period 2007-11

[78] Note: Histogram created using Excel data analysis program; each bin shows frequency from above lower bin value up to and including the bin value.

7.6 UK Industry Measurements on Hydroprocessed Fuels

In support of the introduction of lubricity into the UK jet fuel specification the UK industry tested a number of different hydroprocessed jet fuels using BOCLE ASTM D5001[79]. This showed that 100% hydroprocessed fuel does not always give a high wear scar diameter, Table 8.

Fuel Type	BOCLE WSD (mm)
Hydrofined 1	0.58
Hydrofined 2	0.68
Hydrocracked Kero 1	0.82
Hydrocracked Kero 2	0.76
Hydrocracked Kero 3	0.79
Hydrofined Jet A-1 1	0.84
Hydrofined Jet A-1 2	0.78
Hydrofined Jet A-1 3	0.76
Hydrofined Jet A-1 4	0.80
Hydrofined Jet A-1 5	0.68
Hydrofined Jet A-1 6	0.77
Hydrocracked Jet A-1 1	0.70
Hydrocracked Jet A-1 2	0.66
Hydrocracked Jet A-1 3	0.65

Table 8: BOCLE wear scar diameters for a range of UK sourced hydroprocessed jet fuels

7.7 ASTM Jet for Diesel Task Force

The ASTM D02 J Jet for Diesel Task Force has collected data on 70 samples of jet fuel taken from the Colonial Pipeline. The BOCLE data are shown in Figure 28[80]. The exact origins of the samples are unknown. None of the fuels were subject to clay filtration in the distribution system. Therefore these results represent product direct from the refineries. All results meet the 0.85 mm maximum allowed in Defence Standard 91-91.

[79] G. Rickard and G. Datschefski, "Lubricity Review," Technical report to UK MoD DERA/MSS1/CR990253, January 1999.

[80] R. Gaughan and P. Wells, Presentation to the Jet for Diesel ASTM task force,, ASTM San Francisco, June 2012.

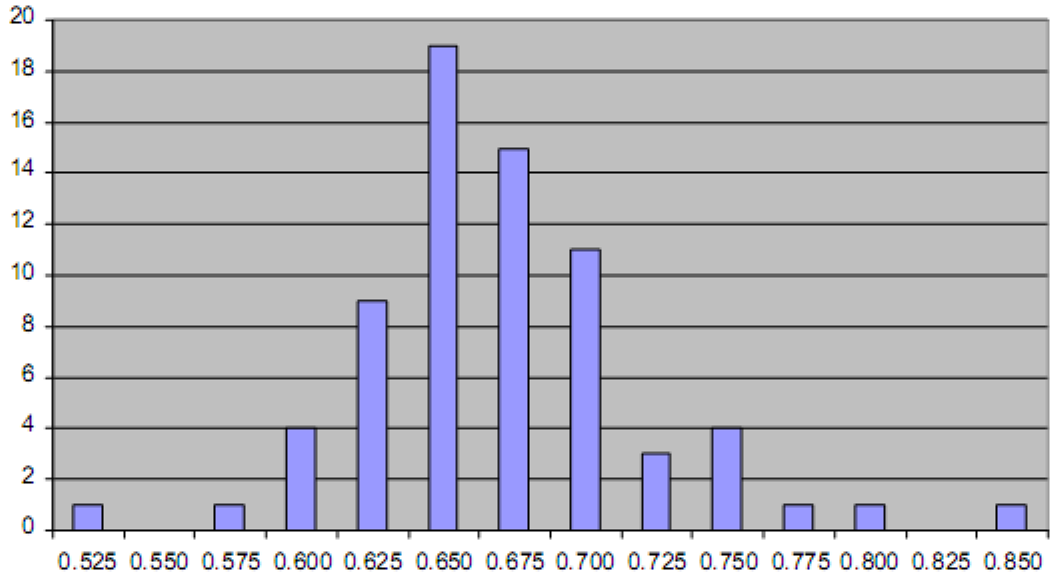

Figure 28: BOCLE data from Colonial Pipeline jet fuel samples

7.8 GE Market Survey

GE monitor market jet fuel quality through the US Air Force Petroleum Agency Into-Plane Contract data and samples from areas where legacy hardware demonstrates the presence of low lubricity fuels. Current Air Force data indicates that fuels with BOCLE WSD's of greater than 0.80 mm appear in about 0.50% of the total tests run over a year, typically 1,400 samples. The Air Force data is predominately obtained in the US (highest portion) and Europe (second highest) with other data collected in the Mid-East and on the Pacific Rim (fewest). For the US the average BOCLE is about 0.68 mm with a 10% variation. However, there appears to be a small number of airports, spread from the Eastern Mid-Atlantic states west along the Gulf coast and up the western seaboard where one sample in the three or four samples taken in a year will have a BOCLE value of greater than 0.80 mm.

For Europe, 2004 – 2009, many low lubricity fuel samples were found in Spain and Italy, with BOCLE results greater than 0.80 mm. A sample of these measurements was reported by BP in 2012, Air Force data having been taken in 2004: Italy – 0.87 mm, 0.88 mm; Hungary – 0.89 mm and Qatar – 0.93mm.

For the Far East, 2008 – 2009, of about 30 airports nine were sampled due to a fuel pump wear problem in a fleet of aircraft operating in the area. BOCLE results were 0.63, 0.80, 0.81, 0.82, 0.84, 0.85, 0.87 and 0.92mm.

Overall, worldwide the lubricity of aviation fuel was found acceptable, BOCLE < 0.75 mm, but with a small number of locations/areas where low lubricity fuels are delivered intermittently or continually.

7.9 Section Summary

- Data on fuel lubricity measurements (BOCLE ASTM D5001) worldwide show small percentages of fuel with >0.85 mm WSD. These appeared to be reduced, outside the US, after the lubricity requirements came into force in Defence Standard 91-91 in year 2000.

- USAF data for years 1996 and 1997, and based on a jet fuel lubricity criteria of 0.65 mm WSD maximum prior to addition of CI/LI, show 32 and 31% of fuels exceeding this value respectively.
- The latest survey data, for years 2007-11, showed only one sample out of 3735 with a wear scar diameter >0.85 mm.

8 Lubricity in Jet Fuel Specifications

8.1 UK Defence Standard 91-91

Following the New Zealand lubricity issue in 1994, the UK MoD was requested by the UK Civil Aviation Authority to include a lubricity requirement in the UK jet fuel specification. The idea behind the requirements that were developed and eventually became part of the specification was to capture most (though not necessarily all) fuels with low lubricity whilst not burdening the industry with testing on the vast majority of product.

The current Defence Standard 91-91 Issue 7 Amendment 2 requires a lubricity wear scar diameter, in accordance with ASTM D5001, of no more than 0.85 mm at the point of manufacture. The requirement to determine lubricity only applies to fuels whose composition is made up of:

a) less than 5% non-hydrotreated components and at least 20% severely hydrotreated components[81], or
b) synthesised fuel components.

The Defence Standard also contains the following information:

> '*Aircraft/engine fuel system components and fuel control units rely on the fuel to lubricate their moving parts. The effectiveness of a jet fuel as a lubricant in such equipment is referred to as its 'lubricity'. Differences in component design and materials result in varying degrees of equipment sensitivity to fuel lubricity. Similarly, jet fuels vary in their level of lubricity. In-service problems experienced have ranged in severity from reductions in pump flow to unexpected mechanical failure leading to in-flight engine shutdown.*
>
> *The chemical and physical properties of jet fuel cause it to be a relatively poor lubricating material under high temperature and high load conditions. Severe hydroprocessing removes trace components, resulting in fuels which tend to have a lower lubricity than straight-run or wet-treated fuels. Lubricity improver additives are widely used in military jet fuels. They have been used occasionally in civil jet fuel to overcome aircraft problems, but only as a temporary remedy while improvements to the fuel system components or changes to fuel were achieved. Because of their polar nature, these additives can have adverse effects on ground-based filtration systems and on fuel/water separation characteristics.*
>
> *Some modern aircraft fuel system components have been and are being designed to operate on poor lubricity fuel. With the participation of the international aviation industry the SAE AE-5B group has revised the procedure for the Low Lubricity Endurance Test for aircraft engine*

[81] Severely hydroprocessed components are defined as those petroleum derived hydrocarbons that have been subjected to a hydrogen partial pressure of greater than 7000 kPa during manufacture.

fuel pumps, ARP 1797. The procedure now specifies that the test fluid used shall produce a wear scar diameter (WSD) between 0.85 and 0.96 mm as measured by ASTM D5001. The introduction of a lubricity requirement maximum of 0.85 mm WSD is to provide a limit to the fuel lubricity which attempts to ensure that future equipment proven against ARP 1797 procedure does not suffer lubricity related problems in use. The requirement only applies to fuels containing more than 95% hydroprocessed material and where at least 20% is severely hydroprocessed and to those fuels that contain a proportion of synthesized material as permitted by this standard. All the fuels which have caused problems have been in this category. It has been noted that not all fuels containing severely hydroprocessed components produce a WSD greater than 0.85 mm and this has been taken into account in setting the requirement.

There are older fuel system components still in use which are more sensitive to fuel lubricity. In these cases the aircraft operator should consult with the equipment manufacturer and fuel supplier to determine the best course of action which may include the use of an approved lubricity additive to enhance the lubricity of a particular fuel, a measure which is already permitted by this standard.'

8.2 US MIL Specifications

MIL-T-83133, 'Military specification, turbine fuel, aviation, kerosine types, NATO F-34 (JP-8), contains no direct specification requirement for lubricity. However, it specifies the mandatory addition of a corrosion inhibitor / lubricity additive. The lubricity additive must be an approved product and comply with the US military specification MIL-I-25017, the addition of the additive is designed to ensure that all JP-8 has a sufficiently high lubricity for US military aircraft (BOCLE wear scar diameter of 0.65 mm maximum). For further details see Section 9.

8.3 ASTM D1655

There is no mandatory requirement within ASTM D1655-13 with respect to lubricity. However, D1655 contains a non-mandatory Appendix which is as follows:

Aircraft/engine fuel system components and fuel control units rely on the fuel to lubricate their sliding parts. The effectiveness of a jet fuel as a lubricant in such equipment is referred to as its lubricity. Differences in fuel system component design and materials result in varying degrees of equipment sensitivity to fuel lubricity. Similarly, jet fuels vary in their level of lubricity. In-service problems experienced have ranged in severity from reductions in pump flow to unexpected mechanical failure leading to in-flight engine shutdown.
The chemical and physical properties of jet fuel cause it to be a relatively poor lubricating material under high temperature and high load conditions. Severe hydroprocessing removes trace components resulting in fuels that tend to have lower lubricity than straight-run or wet-treated fuels. Corrosion inhibitor/lubricity improver additives (see Table 2) are routinely used to improve the lubricity of military fuels and may be

used in civil fuels. These additives vary in efficacy and may be depleted by adsorption on tank and pipe surfaces, so treat rates should be set with care. Because of their polar nature, these additives can have adverse effects on fuel filtration systems and on fuel water separation characteristics. For this reason, it is preferable to avoid adding more of these additives than needed. When adequate jet fuel lubricity performance is achieved solely by additive use (without BOCLE testing or commingling with higher lubricity fuels), the additive concentration should be used at no less than its Minimum Effective Concentration (MEC) from the military Qualified Products List (QPL-25017). These levels are:

CI/LI Additive	*MEC*
HiTEC 580	*15 g/m^3*
Innospec DCI-4A	*9 g/m^3*
Nalco 5403	*12 g/m^3*

Most modern aircraft fuel system components have been designed to operate on low lubricity fuel (Test Method D5001 (BOCLE) wear scar diameter up to 0.85 mm). Other aircraft may have fuel system components that are more sensitive to fuel lubricity. Because low lubricity fuels are commingled with high lubricity fuels in most distribution systems, the resultant fuels no longer have low lubricity. However, problems have occurred when severely hydroprocessed fuel from a single source was the primary supply for sensitive aircraft. Where there are concerns about fuel lubricity, the air frame manufacturer can advise precautionary measures, such as the use of an approved lubricity additive to enhance the lubricity of the fuel.

Test Method D5001 (BOCLE) is a test for assessing fuel lubricity where lower lubricity fuels give larger BOCLE wear scar diameters. BOCLE is used for in-service trouble shooting, lubricity additive evaluation, and in the monitoring of low lubricity test fluid during endurance testing of equipment. However, because the BOCLE may not accurately model all types of wear that cause in-service problems, other methods may be developed to better simulate the type of wear most commonly found in the field.

Regulations are requiring increased production and distribution of ultra low sulfur diesel fuel (15 ppm maximum sulfur content). Diesel fuels are desulfurized to these low levels by severe hydroprocessing, sometimes resulting in very low lubricity fuels. Jet fuel lubricity may be impacted by the increased use of low sulfur diesel fuel, because batches of jet fuel may be made to these ultra-low sulfur levels to maintain efficient production and distribution.

Limited market survey data performed on behalf of the ASTM Jet for Diesel Task Force, Section 7.7, suggests these guidelines are followed for current product. A wider survey might be considered given Industry interest in light of GE findings, Section 7.8.

8.4 ASTM D7566

Fuel certified to D7566-12a, Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (which can be recertified to D1655) is required to have a BOCLE wear scar diameter of 0.85 maximum. This limit is applied to the finished blend of fossil derived jet fuel with synthetic component and presented in Table 1 Part 2- Extended Requirements. In addition, the specification includes the same non-mandatory information as ASTM D1655.

8.5 Section Summary

- Defence Standard 91-91 Issue 7 Amendment 2 addresses lubricity by assessing refining manufacturing process. Where a fuel has a composition of:
    - less than 5% non-hydrotreated components and at least 20% severely hydrotreated components, or
    - includes synthesised fuel components.

  an ASTM D5001 lubricity WSD limit of 0.85 mm maximum is applied. The lubricity requirement was originally included in the Defence Standard to capture most (though not necessarily all) fuels with low lubricity whilst not burdening the industry with testing the vast majority of fuels.
- MIL-T-83133 contains the mandatory addition of corrosion inhibitor / lubricity additive, know to improve fuel lubricity properties.
- ASTM D1655-13 does not have lubricity requirement. However, it contains a statement in the non-mandatory section which states 'Most modern aircraft fuel system components have been designed to operate on low lubricity fuel (Test Method D5001 (BOCLE) wear scar diameter up to 0.85 mm).'
- ASTM D7566-12a includes a lubricity requirement for the finished fossil fuel/synthetic fuel blend of 0.85 mm WSD maximum.

9 Additives

9.1 Performance of Corrosion Inhibitors as Lubricity Improving Additives

Addition of a corrosion inhibitor (CI) to jet fuels began in the US in the early 1950s to tackle the problem of excessive corrosion in ground based fuel. However, after experiencing subsequent filtration problems, the requirement to add CI to JP-4 and JP-5 was withdrawn in 1965. Another spate of operational problems soon followed, this time due to lack of lubricity in fuel-lubricated engine components. The malfunctions were serious enough to prompt reinstatement of CI addition to JP-4 in 1966, since the additive was found to function very satisfactorily as a lubricity agent in fuel, Section 4.1. From that time onwards the value of CIs as lubricity enhancers has been acknowledged, and their use in military fuels has been mandatory for this purpose. In civil fuels, CIs are used for incidents of low lubricity-related failures of fuel system hardware, when they can be relied upon to provide an effective short term remedy, but are not normally used as a permanent solution[82].

The active ingredients of CIs are polar, surface-active, long-chain fatty acids. Typically they comprise varying proportions of the trimer, dimer and monomer linoleic acids; the proportions may be set by the natural source from which they can be made or controlled by synthetic routes, to achieve an acceptable balance with water shedding properties of the fuel. CI products supplied by different manufacturers all contain different proportions of these acid types, and would therefore be expected to show slight differences in their impact on fuel lubrication performance. Comparative performances of additives in the field are understandably difficult to quantify and few examples have been reported. One case history from 1986 concerns USAF operational problems with thirty TF30 engine hydraulic fuel pumps in F-111 aircraft[83]. Investigation of the incidents determined that the problem was due to sensitivity of the pump to fuel lubricity. It was also discovered that the same CI had been used in each case. Addition of a different CI at the Air Force Base fuel terminal prevented further occurrences of excessive wear, and no more pump failures were reported.

In the laboratory there is scope to scrutinise the action of lubricity-enhancing additives in great detail, and there have been many evaluations of commercial CIs in test rigs such as the BOCLE. In that way rankings of relative performance have been obtained. Most investigations have selected a preferred base fluid for testing the additives. Thus the relative effectiveness of eleven CIs from Qualified Products List QPL-25017-9 was evaluated in blends with Shell Sol 71, a paraffinic solvent giving good discrimination[84]. Another favourite test fluid is the paraffinic solvent Isopar M, which has been used on many occasions for studying additive behaviour.

[82] G. Datschefski, C. Lewis, and M.B. Walters, ”Jet Fuel Specification Requirements,” DERA SP-101, 1997.
[83] T.B. Biddleand W.H. Edwards, ”Evaluation of Corrosion Inhibitors as Lubricity Improvers,” AFWAL-TR-88-2036, Jul 1988.
[84] J. Petrarca, ”Aviation Turbine Fuel Lubricity - Evaluation of Corrosion Inhibitors,” AFAPL-TR-75-47, Sept 1975.

The type of base fluid used to evaluate CIs - whether a pure solvent or a clay-treated real fuel - tends to influence the resulting performance of an additive. A comprehensive examination of the products on QPL-25017 was carried out by Pratt & Whitney, when BOCLE performance of each listed additive was evaluated in blends with four base fluids: Isopar M, JP-4, JP-5 and JP-8[85]. The three fuel types were stripped of additives and naturally occurring lubricity enhancers by clay treatment (according to Annex A of ASTM D2550). As expected, the additives exhibited slightly different performance levels depending on which base they were tested in. Figure 29 and Table 9 below show the relevant BOCLE results for WSD at Maximum Allowable Concentration (MAC) for seven of the additives. Based on the average WSD obtained with the four test fuels, these products were ranked in the following order of performance:

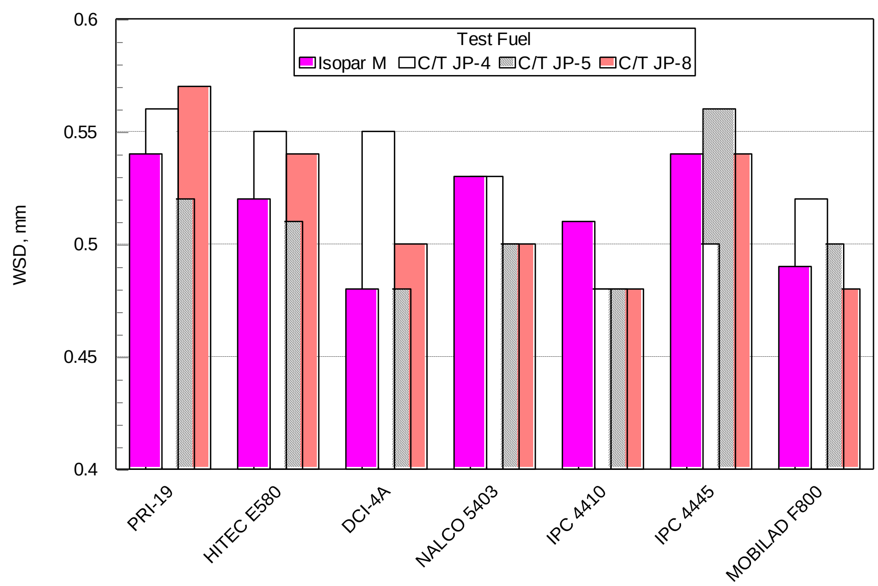

Figure 29: BOCLE data for 7 lubricity improvers tested in four different fuel samples

Corrosion Inhibitor	Average WSD (mm)for all four fuels	Range (mm)
IPC 4410	0.49	0.03
MOBILAD F800	0.50	0.04
DCI-4A	0.50	0.07
NALCO 5403	0.52	0.03
HITEC E580	0.53	0.04
IPC 4445	0.54	0.06
APOLLO PRI-19	0.55	0.05

Table 9: Ranking of lubricity improvers following testing on four different sample fuels

85 T.B. Biddle and W.H. Edwards, :Evaluation of Corrosion Inhibitors as Lubricity Improvers," AFWAL-TR-88-2036, Jul. 1988.

In a study by Shell[86], the performance of CIs in clay-treated white spirit was measured using the TAFLE, which determines lubricity in the scuffing mode. During a test the load is applied in increasing increments until welding of the rubbing contacts takes place. Scuffing is defined as the onset of severe adhesion arising from a breakdown in lubrication. This can be measured by the load at which a substantial increase in friction is observed. Figure 30 shows the results obtained for four commonly-used CI products. There was a substantial increase in scuffing load (better lubricity) for additive treated fuels, and also a difference in additive performance. At maximum dosage, DCI-4A performed best and Apollo PRI-19 relatively badly. Interestingly, parallel tests with the standard (non-scuffing) BOCLE also ranked the same CIs as the best and worst performing ones.

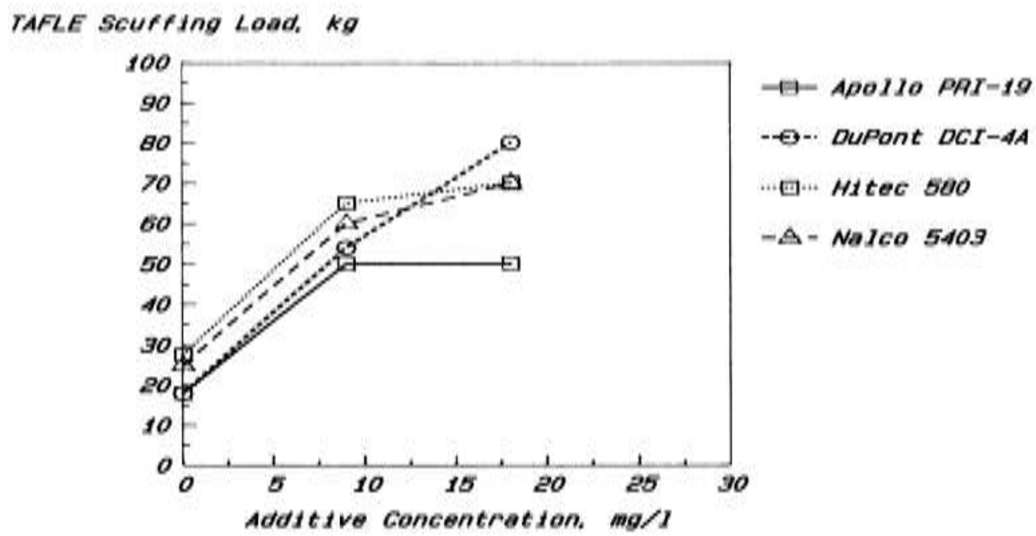

Figure 30: TAFLE scuffing load plotted against additive concentration for four additives.

Increased test temperature appears to have a detrimental effect on CI performance as additive begins to be desorbed from the metal surface. In an extensive series of BOCLE tests[87] Biddle and Edwards generated wear scars at 75 °C, with a range of additive blends that were generally larger than those produced at 25 °C. Unfortunately the familiar curves for 25 °C data showing lubricity improving with additive concentration, were not evident for all tests at 75 °C. Data scatter and lack of repeatability made interpretation of the high temperature results difficult. Figure 31 gives representative data for two CI products - Hitec E580 displaying a clear trend of consistently higher wear at 75 °C, whereas PRI-19 showed less predictable results.

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86 W.G. Blundell and J.W. Hadley, "Lubricity Testing of Corrosion Inhibitors/Lubricity Enhancers Approved for Aviation Turbine Fuel Specifications," MOD Report D/D Eng(PE)/33/26/1, May 1991.

87 T.B. Biddle and W.H. Edwards, "Evaluation of Corrosion Inhibitors as Lubricity Improvers," AFWAL-TR-88-2036, Jul 1988.

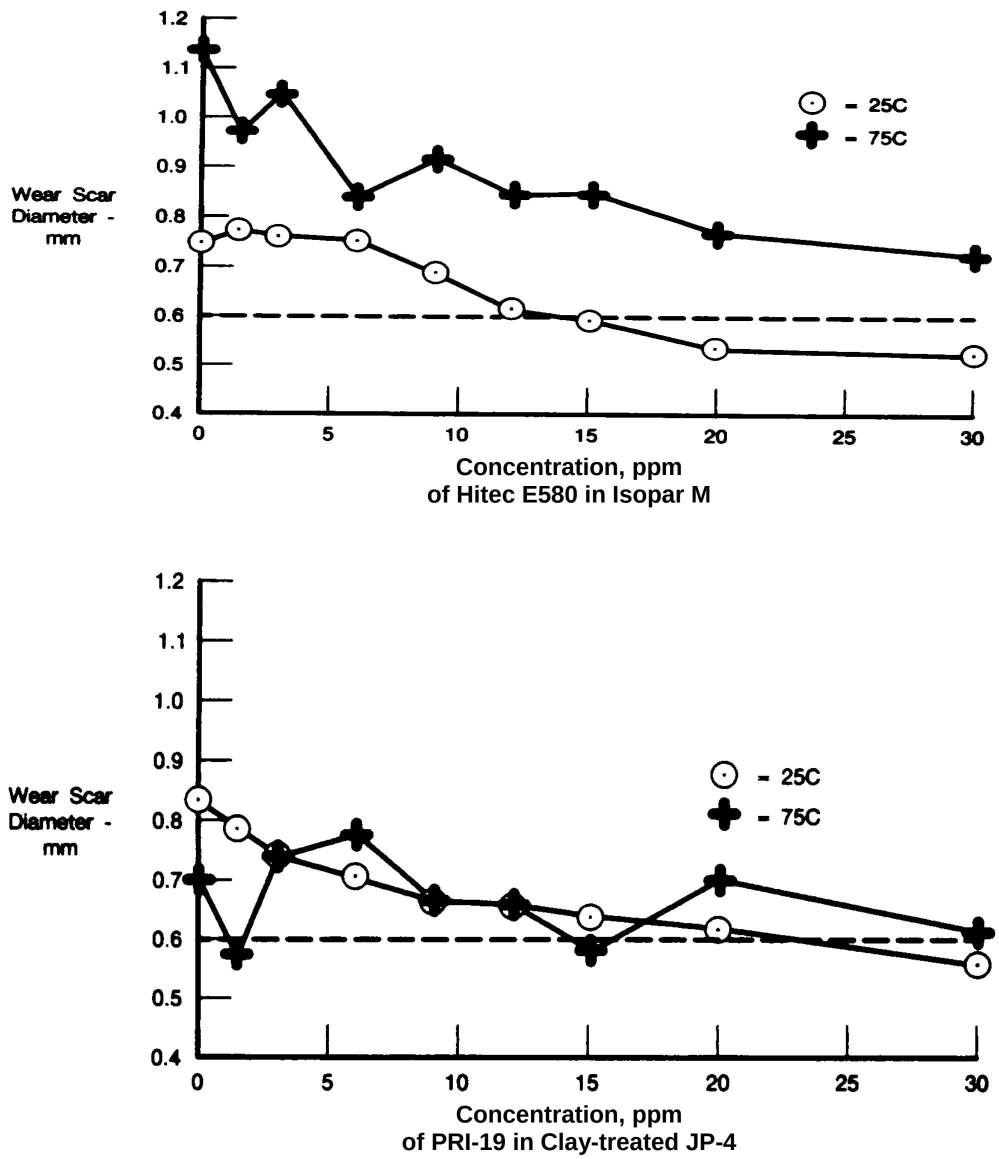

Figure 31: Curves of BOCLE wear scar diameters plotted against additive concentration at 25 and 75°C

9.2 Qualification of Additives

9.2.1 UK Defence Standard 68-251

The first edition of Defence Standard 68-251 specification (then called DERD 2461) included a requirement for additives to meet lubricity-improving criteria as well as demonstrating corrosion inhibiting properties. Lubricating potential was initially measured on a single piston pump installation known as the ‘Teesport rig’, however, this rig was not maintained and became unavailable. The TAFLE, which was developed by Shell Thornton under MoD contract, was then selected as an alternative. This test had potential, showing good correlation with pump tests but, again, became unavailable. At the time, scuffing wear was thought to be a major mode of fuel pump failure, therefore a scuffing wear test was sought for additive approval in addition to the qualification for MIL-I-25017.

A scuffing load BOCLE test was developed by DERA Pyestock and Shell Thornton[88]. The conditions listed in Table 10 were found to be optimal for discrimination and repeatability. This work identified that speed, relative humidity and the loading rate are the critical factors affecting the wear scar.

Variable	Value
Atmosphere	Air
Load	2 kg
Speed	240 rpm
System Pressure	180 kPa
Relative Humidity	45 %
Primary Loading Rate	10 s at 1 kg
Test Duration	2 minutes
Conditioning Time	15 minutes
Fuel Temperature	25°C
Air Temperature	25°C

Table 10: Scuffing load BOCLE test conditions for approval of UK lubricity improving additives

The test was based on the standard ASTM D5001 method; it used the same testing equipment and overall methodology with some modifications. At the end of the test the size of the wear scar generated on the ball was a measure of the scuffing inhibiting property of the additive. The test stated that the precision, repeatability and reproducibility of the method have yet to be established. The specification required the lubricity improving potential to be reported, initially with no specification limits, though these were later defined. The scuffing load BOCLE test was later removed from Defence Standard 68-251 due to lack of support from engine OEMs who favoured the D5001 BOCLE test conditions.

In the UK, lubricity improving additives were not used as pipeline corrosion inhibitors, therefore the corrosion inhibition requirements were removed from the specification to give additive manufacturers the option to develop and approve additives specifically designed to improve lubricity. However, as there was no support from the US militaries for this change, and associated with the cost of additive approval, no new additives were put forward.

9.2.2 MIL-I-25017

In MIL-I-25017 lubricity enhancing performance is assessed in terms of conventional mild wear measured by the standard ASTM D5001 BOCLE method. Minimum Effective

[88] G. Rickard and G. Datschefski, “Lubricity Review,” Technical report to UK MoD DERA/MSS1/CR990253, Jan. 1999.

Concentration (MEC) of lubricity additive is defined as the concentration, in Isopar M low lubricity reference fluid, that gives a wear scar diameter of 0.65 mm or less. The qualification document describes procedures to ensure that the physical and chemical properties of the additive do not adversely affect the storage and use of the fuel.

Unlike the British specification, the MIL-I-25017 specification for corrosion inhibitor additives had no requirement to test for lubricity improving potential until 1989, when the ASTM D5001 BOCLE was first published; this was then embodied in the specification with the MEC criterion of 0.65 mm or less wear scar diameter. All thirteen corrosion inhibitors on the then current Qualified Products List (QPL-25017-15) were re-appraised in terms of the new criterion by suitable testing in Isopar M base fluid[89]. Results showed that MEC and MAC (Maximum Allowable Concentration) values needed to be adjusted for many of the additives in the list to meet the new requirement. The new dosage rates were adopted in the following issue of QPL-25017. This document has been regularly updated with various changes to additives to the present day.

9.2.3 ASTM

Current lubricity improving additives and treat rates in ASTM D1655-13 have been approved via US QPL-25017. For the qualification of new additives, an ASTM approval process has been developed; ASTM D4054 Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives.

9.3 Qualified Additives

ASTM D1655-13 allows the use of three CI/LI additives, HITEC 580, Innospec DCI-4A, and Nalco 5403 as detailed in Table 2. Defence Standard 91-91 Issue 7 Amendment 2 lists 9 lubricity improver additives (LIA) in Section A.5. In addition to the ASTM D1655-13 additives the following are featured: Octel DCI-6A, Tolad 4410, Tolad 351, Unicor J, Nalco 5405 and Spec Aid 8Q22.

9.4 Effect of Other Approved Additives on Lubricity

Only limited work has been reported specifically examining the effect of other approved additives on jet fuel lubricity. As part of the industry development of high temperature thermal stability additives Shell Thornton carried out BOCLE tests on Merox and Hydrofined fuel, both with and without JP-8+100 additive. These studies concluded that the GEBetz +100 additive had no significant impact on lubricity of fuels.

9.5 Loss of Lubricity Additive in Distribution Systems

Lubricity improving additives were originally manufactured as corrosion inhibitors. These are designed to be surface active and adsorb onto pipeline and other fuel system surfaces to inhibit corrosion. The adsorption of the additive onto fuel system surfaces suggests the possibility of additive loss through the distribution system. The authors have some undocumented experience of quantifying the additives for the UK military which showed additive concentrations below specification limits only on rare occasions. It would be expected that systems at equilibrium (where only fuels with lubricity improving additives are used) would see no loss. The loss of additive in non-equilibrium

[89] P.D. Liberio, "Microseparometer and Ball-on-Cylinder Lubricity Evaluator Tests of Corrosion Inhibitor/Lubricity Improver Additives," WRDC-TR-89-2098, Sept. 1989.

systems was investigated by Naval Research Laboratory (NRL)[90], who measured the adsorptive constants for a variety of materials. They concluded that given the worst case surface area to volume ratio for a typical fuel pipeline, 0.4 cm^{-1}, a fuel with a lubricity additive concentration of 9 ppm would lose less than 3% by adsorption onto pipeline walls. This was considered insignificant.

9.6 Section Summary

- Lubricity improving additives approved in Defence Standard 68-251 and US military QPL-25017 are known to increase the lubricity of jet fuels. They feature mostly long chain fatty acid chemistry.
- Three approved additives are cited in ASTM D1655-13 and nine in Defence Standard 91-91 Issue 7 Amendment 2.
- Lubricity improving additives are not widely used in civil jet fuels. The additives were originally designed to be corrosion inhibitors and as such adsorb onto pipeline and other fuel system surfaces. One researcher reported that loss due to surface adsorption would not be significant, at <3%, given a worst case surface area to volume ratio of 0.4 cm^{-1}.

[90] B. Black, D. Hardy, and M. Wetcher, "Determination and use of isothermal adsorption constants of jet fuel lubricity enhancer additives," *Ind. Eng. Chem. Res.*, *28* (5), pp 618–622, American Chemical Society, 1989.

10 Discussion

At the outset of the project four key area were identified for particular focus:

1. To identify which components in aircraft fuel systems/engines are most at risk from lubricity related wear problems.
2. To critically assess the test methods available to measure lubricity with respect to aviation fuel system applications.
3. Compare Defence Standard and ASTM approaches to jet fuel lubricity control for the current and potential future market.
4. Assess the control of lubricity in synthetic jet fuel components detailed in ASTM D7566.

These items are discussed below.

10.1 OEM Hardware at Risk from Low Lubricity Product

Fuel pumps and fuel control units have seen the most issues with fuel lubricity. Often the wear is associated with gear teeth although the failure may be elsewhere in the component because of the distortion and vibration from the worn gears. Failure in aviation fuel pumps systems appears to progress through oxidative corrosion to scuffing as component dimensions become reduced beyond tolerable limits.

10.2 Test Methods

Of seven primary methods evaluated to measure jet fuel lubricity, the BOCLE test, ASTM D5001, was found to offer the best simulation of the oxidative corrosion mechanism cited in Section 10.1. Furthermore, it is sensitive to jet fuel lubricity improving additives.

The use of HFRR for jet fuel may be attractive due to its widespread availability for diesel fuel lubricity testing, however, there appears to be no/little correlation with BOCLE. This is not surprising as wear mechanisms and metallurgy are different. Modifications of the metallurgy and/or test conditions may produce a suitable test method. However, attempts to modify the HFRR have so far, not shown a test suitable for jet fuel lubricity evaluation.

Much historical information has been gathered using BOCLE, and SAE ARP1797 for fuel pump endurance testing uses this method to control fuel quality. The evidence suggests there does not, currently, appear to be anything better for measuring aviation fuel lubricity. In addition, the BOCLE test has been shown to predict the performance of jet fuels containing lubricity enhancers.

Lubricity of fuels is likely to change during distribution. However, the exact changes cannot be quantified. Therefore, producers, handlers, etc. need to assess the risks of lubricity changes when storing/transporting fuel and take actions to mitigate the risks.

10.3 Defence Standard and ASTM Jet Fuel Specifications

Defence Standard and ASTM jet fuel specifications have taken slightly different approaches to fuel lubricity management based on extensive Industry research. Following a number of field issues, a specific BOCLE limit of 0.85 mm maximum has been placed in Defence Standard 91-91 for the measurement and control of lubricity for certain refinery hydrotreating conditions. ASTM D1655 does not mandate a similar requirement but does provide detailed information. However, in ASTM D7566, where manufacturing processes are known to create poor lubricity components, a similar limit to Defence Standard 91-91 has been adopted as mandatory.

With respect to the 0.85mm maximum WSD cited, the general feeling expressed by OEMs was that all new equipment is now designed to operate with fuel having a BOCLE result up to this limit, and is tested to SAE ARP1797 to ensure adequate durability. They believe that while a 0.85 mm WSD is an acceptable upper limit for lubricity, the average lubricity of jet fuel may need to be well below this value (indeed one stated below 0.75 mm WSD) to ensure longevity of equipment. Some older engines/fuel pumps have a 0.65 mm max BOCLE WSD to provide extended pump life, and addition of CI/LI additives to low lubricity fuels is recommended by the manufacturers.

Typical jet fuel production values for BOCLE WSDs are in the region of 0.50-0.65 mm with only a few producers making jet fuel above 0.75 mm WSD. At current fuel lubricity levels the threat of poor lubricity fuel is through single source supply. Where fuel is co-mingled data suggests that lubricity of the resultant batch approaches that of the better lubricity fuel.

For large, fungible markets such as the US the risks of a fuel lubricity related issue are probably low. However, future sulfur levels in jet fuel may be reduced by legislation to as low as 10-15 ppm maximum. Survey data suggests that somewhere below 100 ppm sulfur, BOCLE WSDs start to get close to the 0.85 mm limit when refineries use current hydrotreating or hydrocracking technologies. With no good lubricity fuel to blend with, fuel lubricity might decrease to levels at which OEMs are uncomfortable. Further work is required to understand the magnitude of this effect/if of real operational impact.

Based on the data available, there appears to be no direct correlation to show that a BOCLE result of 0.85 mm max wear scar diameter protects fuel systems. However, there is much evidence to suggest this is a reasonable lubricity requirement:

- Defence Standard 91-91 lubricity requirements, combined with ASTM D1655 non-mandatory requirements, have minimised low lubricity fuels so that current fuels (2007 survey) have BOCLE WSD of ≤0.85 mm and no significant pump wear problems appear to occur with modern aircraft fuel systems. There is no direct evidence that a BOCLE value of 0.85mm WSD limit is suitable for use.

- The lubricity issues in New Zealand during 1994-5 showed that with high BOCLE WSD fuels there were durability issues on equipment which saw a continuous diet of this fuel. Once the fuels were blended to provide lower BOCLE WSD there were no more field problems.

- If used to evaluate new components, SAE ARP1797 can verify minimal wear when using test fuel with a BOCLE wear scar diameter ≥0.85mm.

- OEMs report BOCLE ASTM D5001 correlation with field use.

The risk of low lubricity fuel causing field problems needs to also be considered for both current and future production. Assuming low lubricity fuels which have potential to cause impact have a BOCLE WSD of >0.85 mm, it appears that the risk is currently low because there are so few fuels with such properties. However, the risk is credible, as there may be a single supply of low lubricity fuel (New Zealand case). Furthermore, there appears to be an increasing trend in ultra low sulfur (ULS) jet fuel, which is likely to increase the quantity of low lubricity product. On this basis, regional manufacturing trends and single supply sources need careful consideration. Looking to the future, if jet fuel sulfur limits are reduced in light of environmental legislation, evidence suggests the increase in hydrotreatment use/severity will impact fuel lubricity and understanding is required. With respect to options for specification control, Defence Standard 91-91 and ASTM D7566 already offer helpful guidance. In addition, additives and blending options have been well developed to ensure fit-for-purpose product in the market.

10.4 Synthetic Jet Fuel Components

Synthetic jet fuel components tend to have very poor lubricity because none of the trace species required for the property tend to survive the manufacturing process, even if formed at some early stage. Lubricity is currently controlled in D7566-12a where the final blend of semi-synthetic fuel must have a BOCLE WSD of 0.85 mm maximum. Therefore, all semi-synthetic fuel, even if recertified to D1655 where no BOCLE is required, has a BOCLE WSD of 0.85 mm maximum. As such, synthetic product appears already well controlled with respect to lubricity.

11 Conclusions

11.1 Operating Incidents and Aircraft Fuel System Hardware

While a number of historical incidents related to jet fuel lubricity are readily available (1960/70s military/civil, 1990 New Zealand), recent airline experience was difficult to obtain. Those airlines which replied to the CRC survey reported no incidences of lubricity related problems in recent years. This suggests the fuel property as currently fit-for-purpose in the market.

With respect to OEM hardware, OEMs state the fuel pumps are the critical areas of the fuel system at risk from wear due to poor fuel lubricity. Metallurgy of pumps has been improved over the years and modern equipment is less sensitive to fuel lubricity. However, some older equipment which may be more sensitive is still in use.

Small engines (business, regional, general aviation, helicopters) were reported to be more likely to get a steady diet of a low lubricity fuel than engines used on large commercial transport aircraft, as shown by an incident in New Zealand. This is because small business fleets tend to fly from fixed bases where there may be a single source of supply, versus the large commercial fleet using a broad range of fungible product around the world.

Wear in aircraft fuel systems is unlikely to be described by a single mechanism. However, if wear in gear pumps is considered most important, the following is evident from research:

- the most satisfactory explanation is a simple corrosive wear process, involving the repeated formation and removal of metal oxides during sliding. Oxidative corrosion appeared to be the primary wear mechanism. This is followed by severe adhesive wear and scuffing as the component dimensions were reduced beyond tolerable limits.
- The secondary importance of scuffing is indicated by the fact that corrosion inhibitors have little effect on scuffing resistance, but are still capable of eliminating lubricity problems in aviation fuel systems.

11.2 Test methods

Many mechanised test rigs have been developed over the past 40 years. Most do not simulate the type of wear exhibited in aircraft fuel systems. Data showing correlation of test results with pump wear are scarce.

Of seven methods assess to measure jet fuel lubricity the BOCLE test in accordance with ASTM D5001 exhibits oxidative corrosion type wear to produce a measurable wear scar with sufficient sensitivity to additives and precision.

There is limited information on correlation between BOCLE and fuel pumps wear available in the literature. Rolls Royce and Lucas reported good correlation of BOCLE wear scar diameter to pump wear during testing in the 1980s, however, no data were reported to external groups. Unpublished U.S. federal government research carried out by Southwest Research Institute in the early 1980s appeared to show a linear relationship between BOCLE and scuffing wear with some pumps. Further evidence for the applicability of D5001 is its response to jet fuel lubricity improving additives, which are known to improve fuel lubricity.

From the OEM perspective, a recommended practice is published by the Society of Automotive Engineers (SAE): Aerospace Recommended Practice (ARP) 1797 'Aircraft and Aircraft Engine Fuel Pump Low Lubricity Fluid Endurance Test'. This involves ensuring that a fuel pump can operate sufficiently for 100 hours with a low lubricity fluid (between 0.85 and 0.96 mm BOCLE in accordance with ASTM D5001). While this is recommended it is not clear if all new pumps go through this process. At least one of the major engine manufacturers does not believe that this test protects their hardware sufficiently to allow them to operate on a continuous diet of fuel at 0.85 mm WSD for extended durations.

HFRR, in accordance with ASTM D6079, is widely available in many fuel laboratories for testing automotive diesel fuel lubricity and there is some impetus to use this equipment for jet fuel testing. However, the HFRR shows no correlation with D5001 and no response to additive treatment of fuels. Various parameters within the HFRR are adjustable and it may be possible to modify D6079 to produce a suitable test though nothing convincing has been developed yet. Experience would suggest that test development, requiring multiple laboratories to cooperate, could easily take 5-10 years.

11.3 Fuel Properties and Production

Sulfur content is not directly indicative of lubricity for a given fuel. Poor lubricity is generally linked to the removal of polar materials during hydrotreatment, especially severe hydrotreatment. A very low sulfur fuel is, however, likely to exhibit poor lubricity because of the coincidental removal of polar species during the sulfur removal process. Fuels from non-conventional sources such as synthesised hydrocarbons are generally without polar materials and are also likely to exhibit poor lubricity.

Blending small percentages of straight run or Merox type fuels significantly increases a fuels lubricity. Addition of 5% of such fuel to a low lubricity fuel typically improves the lubricity significantly.

During distribution any co-mingling is likely to improve fuel lubricity. Conversely, clay treatment in the distribution system is likely to remove trace polar materials and could reduce fuel lubricity.

Data on fuel lubricity measurements (ASTM D5001) worldwide showed small percentages of fuel >0.85 mm WSD which appeared to be reduced after the lubricity requirements came into force in Defence Standard 91-91 and wording included in ASTM D1655. Current survey data, for years 2007-11, found only one sample out of 3735 with a WSD >0.85 mm. However, market information also suggests that the quantity of ultra low sulfur jet fuel in the US and the EU is rising which may indicate an erosion of lubricity margin. In addition, pockets of single supply/poor lubricity product may develop.

It is not clear if environmental legislation to reduce sulfur content in jet fuel is likely. However, if this occurs and sulfur levels in fuel are 15 ppm or less, low lubricity product is likely to become more standard in the market. The implications of this require greater understanding.

11.4 Fuel Specifications

Defence Standard 91-91 addresses lubricity by assessing refining processes rather than sulfur content. Defence Standard 91-91 Issue 7 Amendment 2 requires a lubricity wear scar diameter, in accordance with ASTM D5001, of no more than 0.85 mm. However, the requirement to determine lubricity only applies to fuels whose composition is made up of:

- less than 5% non-hydrotreated components and at least 20% severely hydrotreated components, or
- includes synthesised fuel components.

The lubricity requirement was originally included in the Defence Standard to capture most (though not necessarily all) fuels with low lubricity whilst not burdening the industry with testing on the vast majority of fuels.

ASTM D1655-13 does not have a lubricity requirement. However, it contains a statement in the non-mandatory section 'Most modern aircraft fuel system components have been designed to operate on low lubricity fuel (Test Method D5001 (BOCLE) wear scar diameter up to 0.85 mm)' with supporting evidence.

ASTM D7566-12a features a similar lubricity limit to Defence Standard 91-91 of 0.85 mm maximum WSD. This is applied to the finished blend of the synthetic and fossil fuel derived components and is to account for the known poor lubricity of product which has been extensively hydrotreated. Similar supporting evidence is provided as in ASTM D1655.

11.5 Additives

Lubricity improving additives approved in US military QPL-25017 are known to increase the lubricity of jet fuels. They are mostly long chain fatty acid type additives. Three of the approved additives are cited in ASTM D1655-13 and nine in Defence Standard 91-91 Issue 7 Amendment 2.

Lubricity improving additives are not widely used in civil jet fuels. The additives were originally designed to be corrosion inhibitors and as such adsorb onto pipeline and other fuel system surfaces. One researcher reported that loss due to surface adsorption would not be significant (3%) given a worst case surface area to volume ratio of 0.4 cm^{-1}.

12 Recommendations

The following recommendations are proposed:

- The information contained within this report is made available to Industry members via the CRC for further consideration and to airline fuel technical groups to allow informed monitoring of their suppliers.
- Vigilance is maintained with regard to jet fuel lubricity, particularly in regions where there is a single source of supply and extensive hydrotreatment is utilized which may deplete trace polar species from product. This might be actioned as part of an Industry world survey, similar to sulfur, to gather a set of base-line data. For regions where multiple sources of supply/processing routes are available, evidence suggests co-mingling of product helps ensure adequate lubricity.
- If necessary, experimental laboratory test methods for assessment of jet fuel lubricity might be reconsidered with respect to the service duty of fuel system components, to make sure results remain representative.

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