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FUEL LUBRICITY REQUIREMENTS FOR DIESEL INJECTION SYSTEMS

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By

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The U.S. Department of Defense has adopted the single fuel for the battlefield concept. Diesel fuel will be replaced by JP-8/Jet A-1, which has both lower lubricity and viscosity. Currently, the tribological requirements of fuel-lubricated components in the injection system are unknown. As a result, no widely approved lubricity test or standard exists. Similar problems are currently faced in commercial applications where low-sulfur/aromatic fuels are being introduced.

The present study details the wear mechanisms likely to exist with low-lubricity fuels, with particular reference to injection equipment known to be fuel sensitive. The wear mechanism was found to be a function of contact severity and may not be uniquely defined by a single test. A number of potentially viable lubricity tests is suggested, and fuel/additive components are recommended for wear reduction. Pump stand tests are currently underway to study the correlation of the lubricity tests, with full scale testing.

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EXECUTIVE SUMMARY

<u>Problems and Objectives</u>: The use of poor lubricity fuels in United States military ground equipment is causing increased wear in critical fuel-lubricated components. Currently, no recognized standard exists to define the lubricity requirements of the fuel injection systems in compression ignition engines.

<u>Importance of Project</u>: The fuel injection system is central to the reliable operation of compression ignition engines. Use of low-lubricity fuel may have contributed to the increase in pump-related failures seen in the 1990-91 Operation Desert Shield/Storm operations. A standardized bench test that recognizes the fuel lubricity requirements of fuel injection systems is urgently needed.

<u>Technical Approach</u>: A number of possible additives to enhance fuel lubricity were evaluated. The additized fuels were initially studied using the Ball-on-Cylinder Lubricity Evaluator originally developed by the U.S. Air Force. Subsequently, a more detailed test series was developed to reflect the operating environment and metallurgy inside a fuel-sensitive diesel injection pump. Finally, a systematic study of fuel lubricity was undertaken using a wear-mapping technique.

<u>Accomplishments</u>: The Ball-on-Cylinder Lubricity Evaluator (BOCLE) was found to be an accurate wear test, sensitive to the lubricity of fuels, under mild corrosive wear conditions. However, more severe contact conditions would require a modified test that reflects the wear mechanism present. A potentially viable test that reflects these needs was suggested, and fuel/additive components were recommended for pump wear reduction.

<u>Military Impact</u>: The results of this study indicate that use of certain jet fuels is likely to increase pump wear, although hardware modifications are available to alleviate the problem. A minimum fuel lubricity requirement for jet and diesel fuels is urgently needed. The current study highlighted the wear mechanisms present with low-lubricity fuels, with reference to the likely needs of the more critical fuel system components.

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The authors acknowledge the U.S. Army Tank-Automotive Command/AMSTA-RG and Belvoir RDE Center/STRBE-FG, which provided several fuel injection pumps that had failed in military service for BFLRF failure analysis.

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I. INTRODUCTION

To decrease its fuel logistics burden, the Department of Defense (DOD) is advancing the use of a single fuel on the battlefield.(1)* To this end, Aviation Turbine Fuel, Military Grade JP-8 (NATO Code F-34), JP-5 (F-44), or Commercial Jet A-1 (F-35) is replacing diesel fuel (DF-2) in selected theaters of operations. Prior to this directive (1), JP-8 was specified as an alternative fuel for use in compression ignition engines. As such, no significant degradation of performance or service life should occur as a result of operating diesel equipment on JP-8.

The DOD and North Atlantic Treaty Organization (NATO) "single fuel" directives (1,2) are supported by many years of engine testing (3-5) and more recently by an ongoing JP-8 demonstration at Fort Bliss, TX.(6) Some deterioration of Stanadyne rotary fuel injection pumps (Model DB2) fitted to a General Motors (GM) 6.2-liter engine was observed in a 210-hour laboratory dynamometer test (7) and in a laboratory pump rig evaluation.(8) However, this deterioration was not evident in a subsequent 400-hour laboratory dynamometer test (9), nor in a 10,000-mile road test (10) with M1028 Commercial Utility Cargo Vehicles (CUCV) at the Mesa Arizona Proving Ground.

Increased equipment use associated with the 1990-1991 Operation Desert Shield/Storm in Saudi Arabia caused a sharp rise in the occurrence of injection pump failures. The Stanadyne rotary fuel injection pump is associated with most of the failures. Of the equipment currently in service with the U.S. military, the Stanadyne fuel injection pump appears to be the most sensitive to low-lubricity fuel. For this reason, the wear mechanisms present in the Stanadyne pump were singled out as the basis for the current study.

II. OBJECTIVES

The program had several objectives. Because of the ongoing Operation Desert Shield/Storm, the most immediate objective was to develop a rapid screening of fuel additives and lubricants that

* Underscored numbers in parentheses refer to the list of references at the end of this report.

could serve as a lubricity improver for Jet A-1 fuel. The long-term objectives of the project are to develop bench tests that reflect the lubricity requirements of the fuel injection system. This objective will probably require a scuffing load test to define the ultimate load-carrying capability of the fuel. A series of pump stand tests will be completed with neat and additized fuels to provide baseline data for correlation with the bench tests.

This document primarily reports on the efforts toward accomplishing the first objective. Additional work on the remaining objectives is ongoing and will be reported upon completion of the tasks.

III. BACKGROUND

A. Fuel Lubricity

In most fluids, air is beneficial to the formation of an effective boundary layer. (11) However, the lack of polar compounds and reactive species in highly refined fuels allows formation of an oxide layer on metallic surfaces. According to the Pilling-Bedworth rule (12), the oxides of iron do not adhere strongly to the base material. The weaker surface layer is repeatedly formed and removed during sliding contact to produce a high material removal rate. If the applied load is sufficiently great, failure of the surface layers will occur, allowing adhesive welding between the metallic substrates. This catastrophic form of adhesive wear is commonly known as scuffing and is distinct from the milder oxidative mechanism. Weak oxide layers that promote wear under mild conditions probably also serve to separate the bulk materials and prevent adhesive scuffing.

In aviation, problems associated with poor fuel lubricity may be traced back to the 1960s.(13-17) In the present context, a fluid's friction and wear characteristics in a rubbing system are synonymous with the term "lubricity." This means that low friction and wear relates to **high** lubricity, and severe friction and wear relates to **low** lubricity. Increasing severity in the refining process removed many of the polar compounds necessary to form an effective boundary film. Among the commonly used low-lubricity fuels are Jet A-1 and JP-8. Jet A-1 is the industry standard aviation fuel, used worldwide by commercial airlines. It is similar to Jet A, but has a lower freeze point (-47°C versus -40°C). Jet A-1 normally contains no lubricity additives and consists solely of kerosene fractions. JP-8 is equivalent to Jet A-1, with the following mandatory inhibitors:

a) Fuel system icing inhibitor
b) Static dissipator additive
c) Corrosion inhibitor.

It is generally agreed that the icing inhibitor and the antistatic additive have no appreciable effect on lubricity.(18)

B. Evaluation and Measurement of Fuel Lubricity

To qualitatively measure fuel lubricity, the U.S. Air Force adopted the ball-on-cylinder test configuration, originally pioneered by Furey.(19) The ball-on-cylinder device, commonly known as the BOCLE (Ball-on-Cylinder Lubricity Evaluator), has proven to be sensitive to the small amounts of corrosion inhibitor necessary to improve lubricity. The BOCLE test provides a lightly loaded contact, in which the oxide layers are removed without introducing alternative wear mechanisms, such as adhesion or severe abrasion between the bulk materials.(11) Many conventional scuffing and wear tests are too severe to differentiate between the poor lubricities of different fuels.(20,21) After slight modification, the BOCLE was accepted as ASTM Method D 5001, "Test Method for Measurement of Lubricity of Aviation Turbine Fuels by the Ball-on-Cylinder Lubricity Evaluator (BOCLE)," (22) and is now the widely accepted lubricity test for aviation fuels.

In the standard BOCLE test, the average wear scar diameter formed between the test specimens is taken as an indicator of fuel lubricity. Currently, no specification exists for the level of lubricity required to meet the needs of the fuel injection systems on compression ignition equipment. The introduction of low-sulfur/aromatic diesel in response to impending legislation to reduce exhaust emissions is expected to promote increased wear in civilian equipment. The Society of Automotive Engineers has formed a committee to address the lubricity requirements of diesel injection systems. Both the initial meeting of the committee and an open forum presentation held in February 1991 emphasized the urgency of the problem. A number of pump manufacturers stated that equipment failures using certain fuels have already been reported in Canada and Japan.

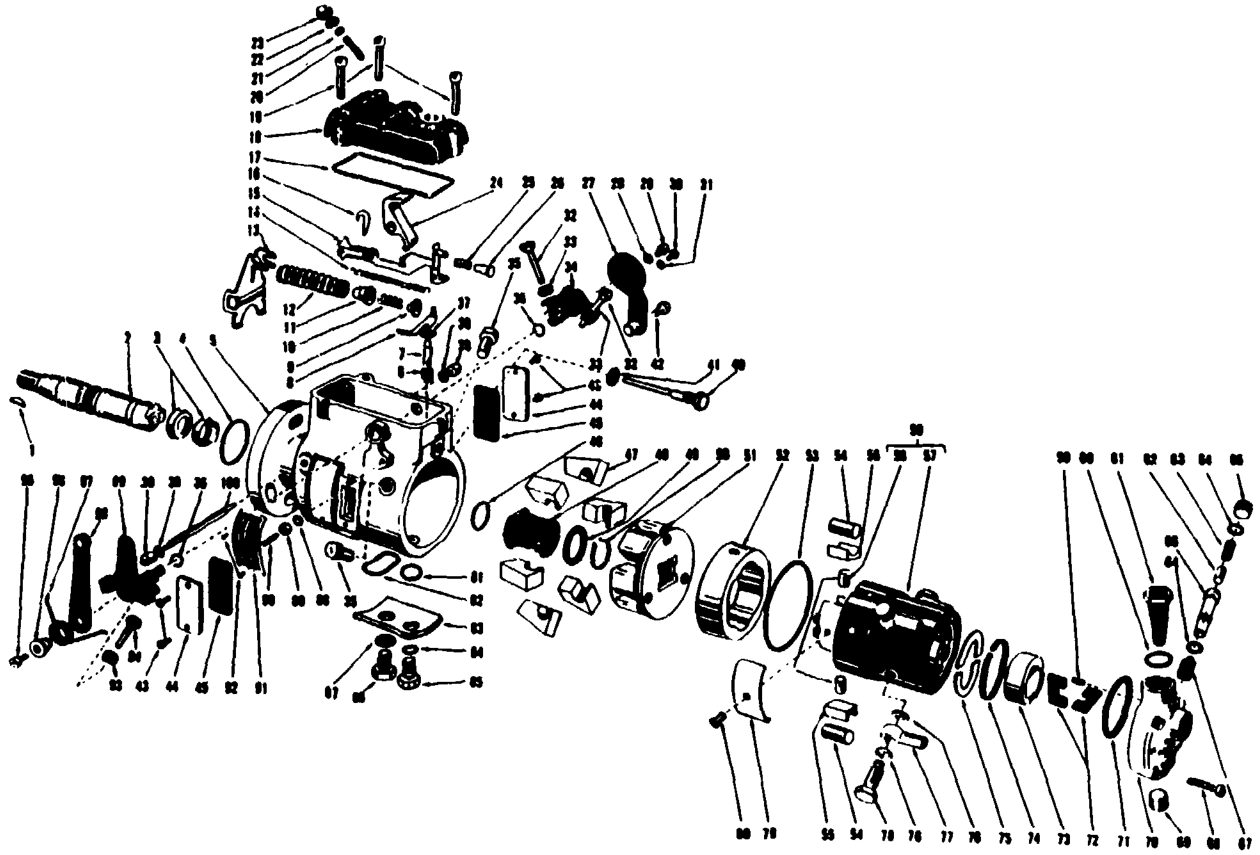
C. The Stanadyne Fuel Injection Pump

Of the equipment currently in service with the United States military, the Stanadyne rotary fuel injection pump appears to be the most sensitive to poor fuel lubricity. For this reason, the wear mechanisms present in the Stanadyne pump were singled out as the basis for the current study.

An exploded view of the Stanadyne model DBM pump is shown in Fig. 1. The most common failure mechanism with the Stanadyne pump appears to be seizure between the rotor and housing, close to the transfer pump. Under normal conditions, these parts should be separated by a hydrodynamic film. The manufacturer indicates that this type of failure is normally due to excessive side thrust in the transfer pump area, caused by sticking of the transfer blades or excess transfer pump pressure.(23) Due to its lower viscosity, JP-8/Jet A-1 forms a weaker hydrodynamic film than DF-2 fuel. Several pump tests were performed to determine the transfer pump pressure required to cause seizure in the above manner. These tests, discussed in Appendix A, used Jet A-1 fuel at temperatures similar to those expected to exist in practical application. However, none of the three pumps failed, even when pressures greater than twice the maximum recommended by the manufacturer were applied.

The fact that none of the pumps failed during the bench tests indicates that the lower viscosity of Jet A-1 is probably not the primary cause of failure, i.e., the hydrodynamic film is unlikely to fail during normal operation. Failure of the hydrodynamic film is more likely to occur as a secondary effect, as a result of abnormal loads created in another area of the pump.

Previously, a number of failed Stanadyne pumps from diesel engine driven mobile power generator sets were examined at the Belvoir Fuels and Lubricants Research Facility.(24) The



1. KEY, drive shaft
2. SHAFT, drive
3. SEAL, drive shaft
4. SEAL, pilot tube
5. HOUSING ASSEMBLY, pump
6. SPRING, metering valve
7. VALVE, metering
8. ARM ASSEMBLY, metering valve
9. GUIDE, idling spring
10. SPRING, idling
11. RETAINER, spring
12. SPRING, governor control
13. ARM, governor
14. SPRING, governor linkage
15. HOOK ASSEMBLY, governor linkage
16. CAM, shut-off
17. GASKET, control cover
18. COVER, governor control
19. SCREW, cover hold-down
20. SCREW, low idle adjusting
21. SEAL, low idle adj. screw
22. WASHER, low idle adj. screw
23. NUT, low idle adj. screw
24. LEVER, throttle shaft
25. SPRING, damper
26. SLEEVE, damper
27. LEVER ASSEMBLY, adj. shut-off
28. LOCKWASHER, adj. shut-off lever ret. screw
29. SCREW, adj. shut-off lever retaining
30. SCREW, adj. shut-off lever positioning
31. LOCKWASHER, adj. shut-off lever pos. screw
32. SCREW, shut-off lever adjusting
33. NUT, adjusting screw
34. SHAFT ASSEMBLY, shut-off
35. SCREW, head locking
36. SEAL, shaft
37. SHIM, metering valve
38. SEAL, pivot shaft
39. NUT, pivot shaft retainer
40. STUD, guide
41. WASHER, guide stud
42. SCREW, stop lever fitting
43. SCREW, timing line cover
44. COVER, timing line
45. GASKET, timing line cover
46. RING, drive shaft retaining
47. WEIGHT, governor
48. SLEEVE, governor thrust
49. WASHER, governor sleeve thrust
50. RING, governor cage retaining
51. RETAINER ASSEMBLY, governor weight
52. CAM RING
53. SEAL, hydraulic head
54. ROLLER, cam
55. SHOE, cam roller
56. PLUNGER, rotor
57. HEAD AND ROTOR, hydraulic
58. HYDRAULIC HEAD AND ROTOR ASSEMBLY
59. ROLLPIN, end plate locating
60. SEAL, filter cap
61. CAP & FILTER ELEMENT ASSEMBLY
62. PISTON, regulating
63. SPRING, regulating
64. SEAL, end plate sleeve
65. PLUG, end plate
66. SLEEVE, end plate
67. SPRING, plunger retaining
68. SCREW, end plate
69. PLUG, end plate pipe
70. PLATE, end
71. SEAL, transfer pump
72. BLADE, transfer pump
73. LINER, transfer pump
74. RING, rotor retainer
75. RETAINER, rotor
76. WASHER, fuel line connector screw
77. CONNECTOR, fuel line
78. SCREW, fuel line connector
79. SPRING, leaf
80. SCREW, leaf spring adjusting
81. SEAL, head locating screw
82. SEAL, cam hole
83. PLATE, cam locating
84. SEAL, head locating screw
85. SCREW, head locating
86. SCREW, cam locating
87. WASHER, cam locating screw
88. SEAL, torque screw
89. NUT, torque screw
90. SCREW, torque
91. PLATE, name
92. SCREW, name plate
93. NUT, high idle adjusting screw
94. SCREW, high idle adjusting
95. SCREW, throttle lever retaining
96. RETAINER, throttle lever spring
97. SPRING, throttle lever
98. LEVER ASSEMBLY, throttle shaft
99. SHAFT ASSEMBLY, throttle
100. SHAFT, governor arm pivot

Figure 1. Exploded view of the Stanadyne DBM fuel injection pump
(Note: This figure was taken from the Stanadyne operation manual.)

results of that study indicated that none of the failures could be directly attributed to the use of Jet A-1 fuel. However, a systematic study of the pump components indicated that certain areas are particularly wear prone. A qualitative estimate of the wear present on critical components from a number of used pumps is provided in Appendix B.

In general, the transfer pump vanes and the drive tang (which connects the pump rotor to the input shaft) are more severely worn than the remainder of the pump. The manufacturer produces an "arctic" conversion kit that replaces these parts when the pump is continually used with low-lubricity fuel. This conversion is commonly used in arctic conditions, during which DF-1/DF-A/Jet A-1 is available. Severe drive tang wear will affect the injection timing and reduce pump performance, but should not induce catastrophic pump failure. However, problems in the transfer pump are known to cause seizure of the rotor (23), which is the commonly observed failure mode that has occurred in Saudi Arabia. It is significant that the improved metallurgy of the arctic parts is sufficient to prevent wear under low-lubricity conditions. In addition, the highly loaded hydraulic head shows no sign of wear, indicating that a metallurgical design "fix" is possible.

Examination of a number of highly worn transfer pump vanes from pumps operated on Jet A-1 in Saudi Arabia indicated that the worn surfaces are polished and largely free of mechanical deformation. The condition of these surfaces is consistent with the topography normally produced by a corrosive wear mechanism. However, Stanadyne provided vanes from failed pumps that showed evidence of scuffing wear between the transfer pump vane and liner. These components are reported to have operated for less than 10 hours on low-lubricity fuel.

IV. TECHNICAL APPROACH

As an immediate "fix," a range of possible lubricity additives was evaluated using the standard BOCLE test. However, additive effectiveness is influenced by variations in metallurgy, loading, temperature, and even humidity, all of which are held constant in the standard test. As a result, the more promising candidates from the initial evaluation were tested at a wide range of conditions using both the BOCLE (ASTM D 5001) and Cameron-Plint wear test apparatus.

To obtain a better understanding of the effects of test severity on the wear process, a wear-mapping technique was developed. Results obtained from the Cameron-Plint wear tests were used to characterize wear as a function of two simultaneous variables. The results delineate the useful application range of sliding contacts lubricated with each fuel. In particular, the scuffing load capacity of each fuel/additive combination is clearly demonstrated.

Finally, a modified BOCLE technique capable of determining the scuffing load capability of various fuels was evaluated. The initial results obtained using the revised methodology were encouraging but demonstrated relatively poor repeatability.

The above tests were performed using U.S. Army-supplied Reference No. 2 diesel fuel (Cat 1-H) (25), JP-8 (26), and Jet A-1 aviation turbine fuel.(27) In addition, a range of Saudi Arabian refined diesel and Jet A-1 fuels used by the U.S. Military Forces in Saudi Arabia was obtained. Selected physical and chemical properties of each fuel are summarized in Appendix C.

V. DISCUSSION OF RESULTS

A. Initial Lubricity Additive Evaluation in BOCLE

A number of potential additive packages were evaluated using the standard BOCLE test procedure as delineated in ASTM D 5001. The BOCLE used in this evaluation was capable of continuous measurement of both friction coefficient and contact resistance during testing. The fuel used was U.S. Army-procured Jet A-1 (Lab No. AL-19346-F) with the physical and chemical properties detailed in Appendix C. The fuel was clay treated in accordance with ASTM D 3948, "Method for Determining Water Separation Characteristics of Aviation Turbine Fuels by Portable Separometer in the Field." Clay-treating strips the fuel of possible additives, naturally occurring lubricity agents (polar compounds), and contaminants. The resulting fuel provides a more severe environment in which to evaluate the effectiveness of the additives. Clay-treated Jet A-1 fuel produced a wear scar diameter of 0.72 mm.

Two distinct categories of additive were examined: a) those specifically designed as fuel additives (not necessarily to improve lubricity) and b) various lubricants/fluids generally available in the theater. The additives were blended into the base fuel at the manufacturer's recommended dosage as given in TABLE 1. The remaining fluids, detailed in TABLE 2, were added to the fuel at 1, 1.5, and 2 vol%, based upon feedback from field personnel deployed in Saudi Arabia.

TABLE 1. Fuel Additives Evaluated in BOCLE Tests

Purpose	Brand Name	Military Specification	Recommended Concentration (mg/L)
Multifunctional	FOA-15	--	71
Corrosion Inhibitor	DCI-4A	MIL-I-25017 (28)	15
Biocide	BIOBOR-JF	--	227
Stabilizer	FOA-15 + BIOBOR-JF	MIL-S-53021 (29)	71 & 227
Corrosion Inhibitor	Unicor J	MIL-I-25017	9
Lubricity Additive	PETROLITE EX1 603	--	300
Lubricity Additive	PETROLITE 91-57695	--	300
Lubricity Additive	PETROLITE 90-	--	300
Corrosion Inhibitor	Nalco 5405	MIL-S-25017	11
Corrosion Inhibitor	Unicor J	MIL-S-25017	9
Corrosion Inhibitor	IPC-4410	MIL-S-25017	9
Corrosion Inhibitor	IPC-4410	MIL-I-25017	9
Corrosion Inhibitor	Nalco 5405	MIL-I-25017	11

TABLE 2. Lubricant/Fluid Products Evaluated in BOCLE Tests

Purpose	Brand Name	Military Specification
Lubricating Oil, Engine	Shell — Fire and Ice	MIL-L-2104 (30)
Lubricating Oil, Gear	Valvoline	MIL-L-2105 (31)
Lubricating Oil, Preservative	--	MIL-L-3150 (32)
Lubricating Oil, Turbine Engine	Aeroshell	MIL-L-23699 (33)
Hydraulic Fluid	Bray	MIL-H-46170 (34)
Transmission Fluid	DEXRON-II	NSN 9150-00-698-2342
Two-Cycle Motor Oil	--	--

The results obtained from the BOCLE tests are shown in Figs. 2 and 3. The results obtained for 0.3 wt% sulfur [di-*tert*-butyl disulfide (TBDS)] added to the clay-treated Jet A-1 fuel are included in Fig. 2. Clearly, sulfur increases the wear rate under these conditions. Some of the lubricants generally available in the theater were successful in reducing wear. However, the combination of FOA-15 and BIOBOR-JF appears to act synergistically to significantly reduce wear. A strong

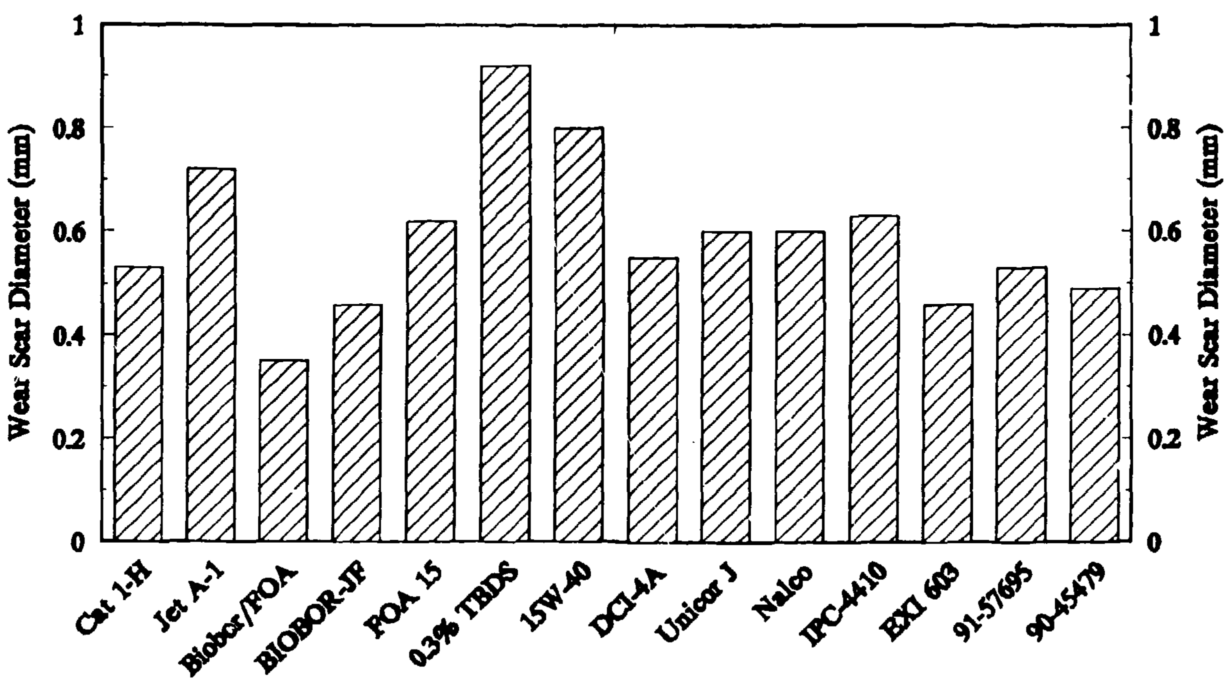


Figure 2. Results of BOCLE wear tests on fuel additives

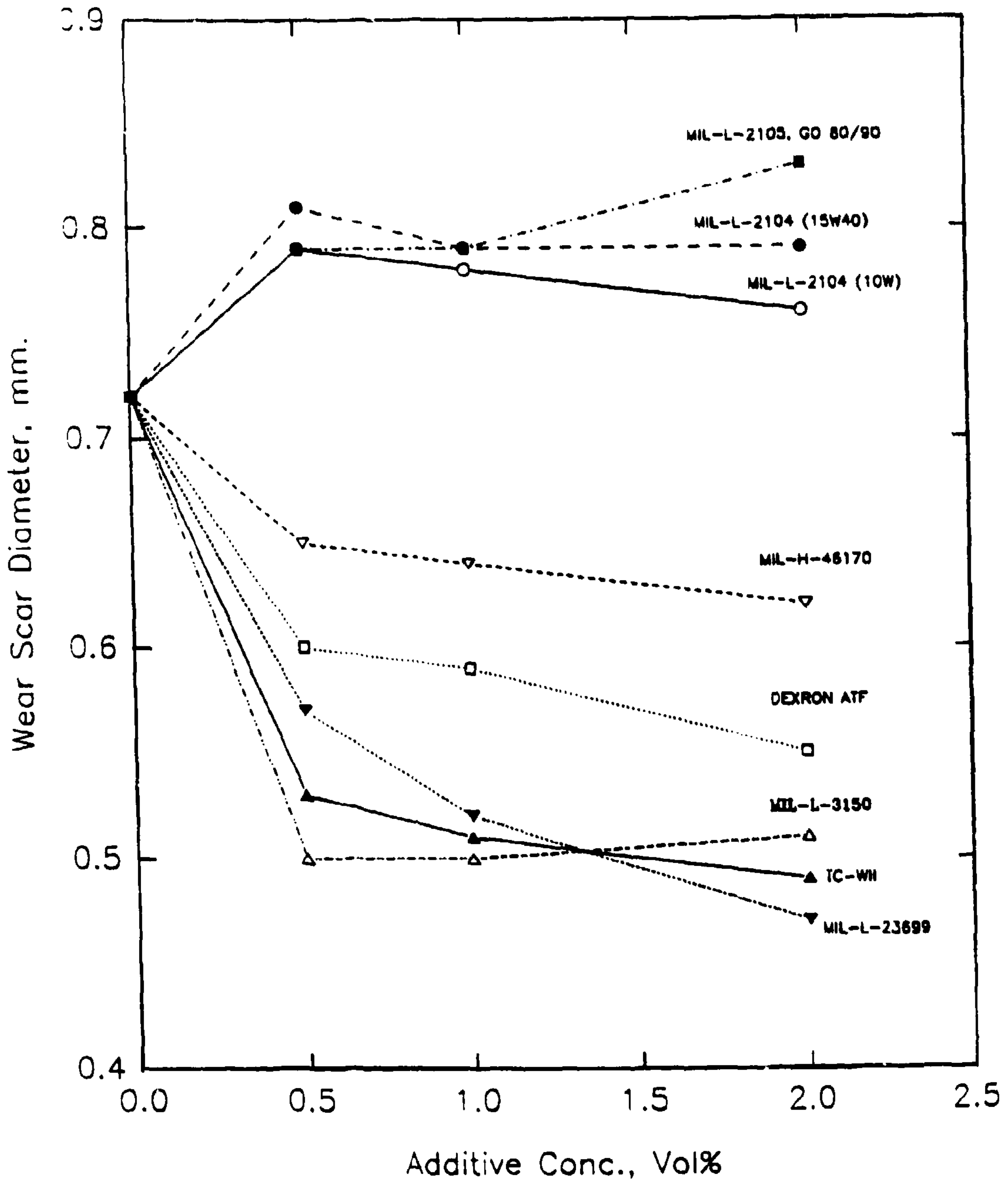


Figure 3. **Results of BOCLE wear tests on lubricant/fluid products available in Saudi Arabia**

contact resistance was measured with this combination, indicating the presence of a boundaryfilm. BIOBOR-JF and FOA-15 are qualified under MIL-S-53021 (29), for use in diesel fuels meeting the requirements of VV-F-800 intended for intermediate or long-term storage.(35) The test results for BIOBOR-JF/FOA-15 in clay-treated Jet A-1 were repeated for two different batches of additive, with similar results in each instance.

FOA-15 is a multifunctional additive and is known to be a blend of four compounds. One of the compounds is similar to AFA-1, and another is known as FOA-3. The remaining compounds are proprietary. AFA-1 and FOA-3 were obtained and tested using the standard BOCLE test but produced little wear protection when used alone. A number of other products are also qualified under MIL-S-53021. Each of these additives was evaluated in clay-treated Jet A-1 at the manufacturer's suggested concentration. However, none of the remaining additives qualified under MIL-S-53021 was successful in reducing wear to the extent produced by the BIOBOR-JF/FOA-15 combination. BIOBOR-JF is approved for use by a number of turbine engine manufacturers.(36)

DCI-4A (MIL-I-25017) (28) is used by the U.S. Air Force as a corrosion inhibitor/lubricity additive. DCI-4A reduced the wear rate seen in the standard BOCLE test, but was less effective than the BIOBOR-JF/FOA-15 combination.

The addition of gear oil or engine oils to Jet A-1 actually increases wear as shown in Fig. 3. The common practice of field personnel to add quantities of these fluids to the fuel is clearly undesirable. In addition, secondary performance problems are likely to occur as described in Reference 37.

1. Effect of Additive Concentration

Both DCI-4A and the BIOBOR-JF/FOA-15 blend were evaluated at a range of concentrations in clay-treated Jet A-1, using the standard BOCLE test methodology. (Note: The manufacturer's recommended dosage for DCI-4A is 15 mg/L, while the dosage rates for BIOBOR-JF/FOA-15 are 227 and 71 mg/L, respectively.) The wear scar produced by the MIL-S-53021 blend is relatively insensitive to concentrations lower than that suggested by the manufacturer, as shown in Fig. 4. (The concentration of BIOBOR-JF/FOA-15 plotted is the sum total of both additives.) DCI-4A is less effective than BIOBOR-JF/FOA-15 at all but the lowest concentrations.

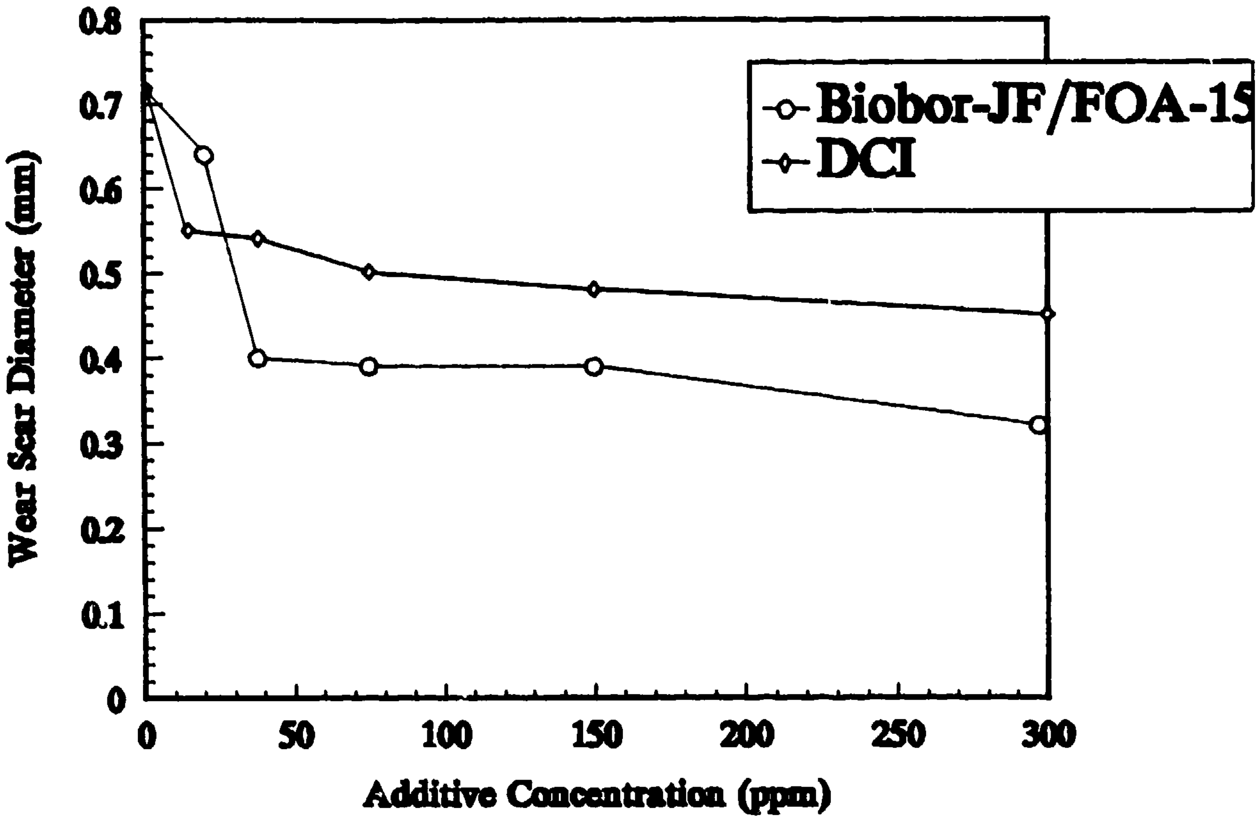


Figure 4. Effect of additive concentration on standard BOCLE test

2. Effect of Temperature on Additive Effectiveness

BOCLE tests were carried out at temperatures between 0° and 90°C with clay-treated Jet A-1, producing the results shown in Fig. 5. Tests were run on clay-treated Jet A-1 and JP-8 for comparison. As the tests were not carried out at 25°C, they deviate from the ASTM test standard. In addition, the fuel was not aerated before each test, as is specified in the standard. This variation helped minimize loss of lighter fractions from the fuel, which has a flash point of 44°C.

Erratic test results were achieved for clay-treated Jet A-1 at temperatures above approximately 50°C. The predictable curves exhibited by the additized fuels were not apparent. Previous workers have also observed this effect (38) and suggested that it may be due to competition

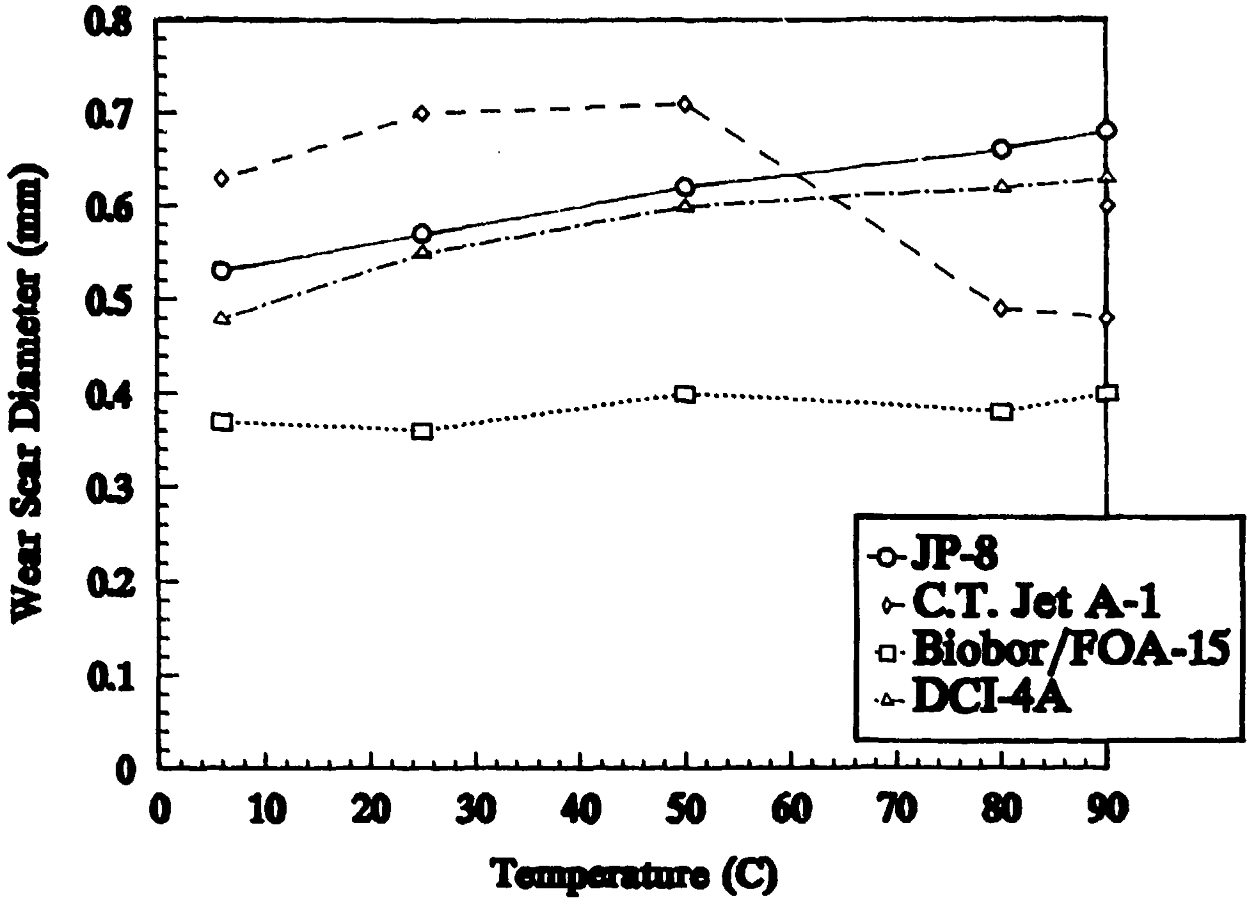


Figure 5. Effect of temperature on BOCLE wear test results

between increased rates of fuel oxidation and surface corrosion at high temperatures. Fuel oxidation reactions form various oxygenated species (i.e., carboxylic acids, aldehydes, alcohols, etc.) that, because of their polar nature, act as good lubricity agents.

Jet A-1 containing DCI-4A and JP-8 produced very similar results. This similiarity is not unexpected as JP-8 contains a mandatory corrosion inhibitor. BIOBOR-JF/FOA-15 appears unaffected by increasing temperature and is more effective than DCI-4A over the temperature range studied.

3. Effect of Humidity on Lubricity Additives

BOCLE wear tests were carried out with DCI-4A as well as BIOBOR-JF/FOA-15 in clay-treated Jet A-1 as a function of humidity. Tests were also carried out using neat clay-treated Jet A-1 and Reference No. 2 diesel fuel (Cat 1-H) for comparison. The results are plotted in Fig. 6 and indicate that the wear scars formed with Cat 1-H and Jet A-1 containing DCI-4A are almost independent of moisture content. DCI-4A has no effect on the wear rate of Jet A-1 at 0 percent humidity. By comparison, the wear rate of both unadditized fuel and the BIOBOR-JF/FOA-15 treated fuel is highly dependent on humidity. At high humidities, some condensation was visible in the bottom of the fuel bath. The effects of free moisture on wear rate and test repeatability are unknown.

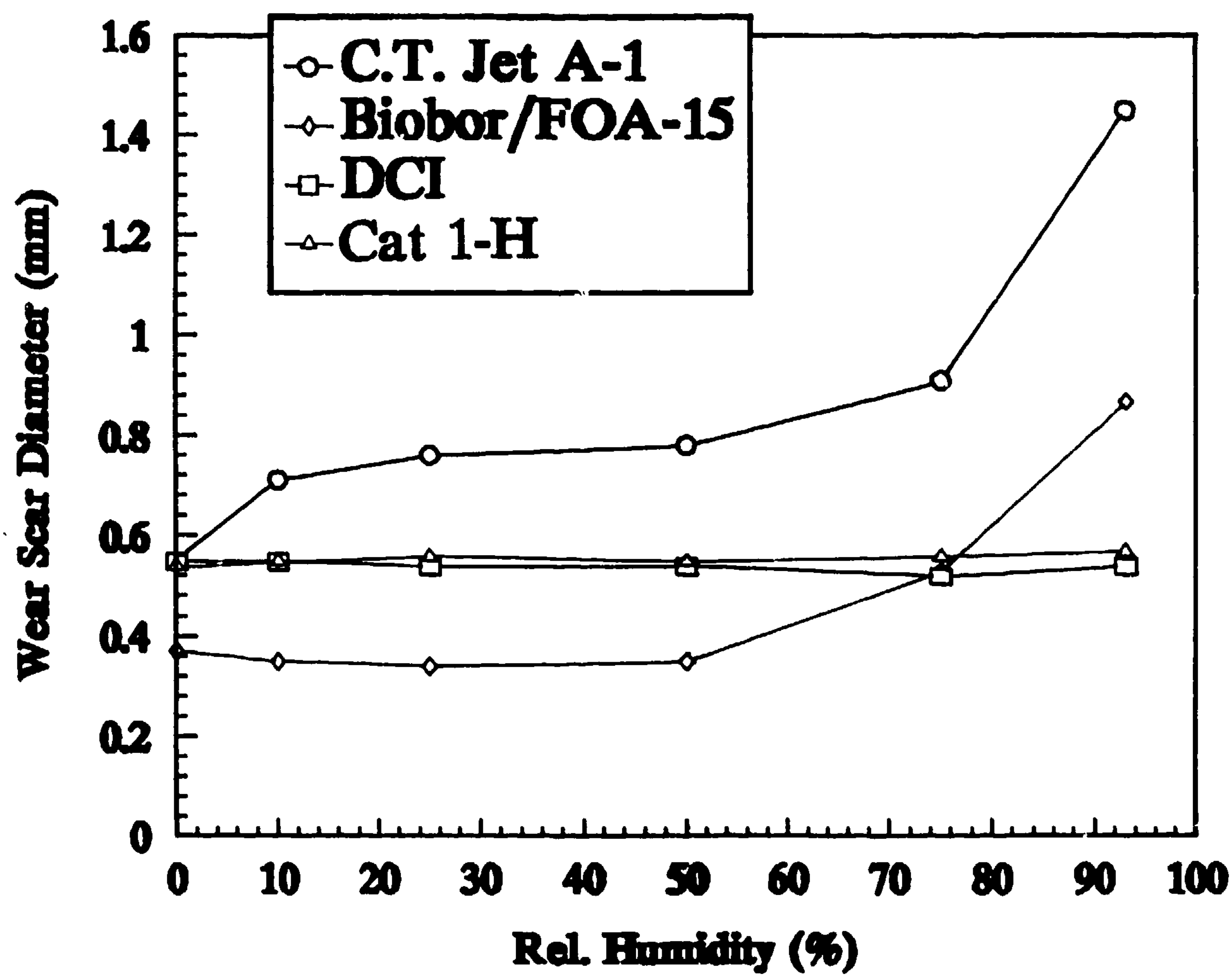


Figure 6. Effect of humidity on BOCLE wear test results

Most lubricity agents are believed to act by competing with oxygen or water vapor for reaction sites on the metallic surface. In the absence of polar compounds in the fuel, oxygen and water are free to react with the nascent metal surfaces formed during the wear process. As a result, the wear rates associated with low-lubricity fuels are particularly sensitive to the levels of oxygen and humidity present, while more lubricous fuels (such as diesel) are almost insensitive to the test atmosphere. The reason for the large increase in wear with BIOBOR-JF/FOA-15 at high humidity levels is unknown.

4. Additive Effectiveness in Different Jet Fuels

A range of Jet A-1 fuels was obtained from Saudi Arabia, similar to those used during Operation Desert Shield. Information on each fuel is provided in Appendix C. Results from standard BOCLE wear tests both with and without the DCI-4A (15 mg/L) and BIOBOR-JF/FOA-15 (227/71 mg/L, respectively) additives are provided in Fig. 7. It should be noted that the above

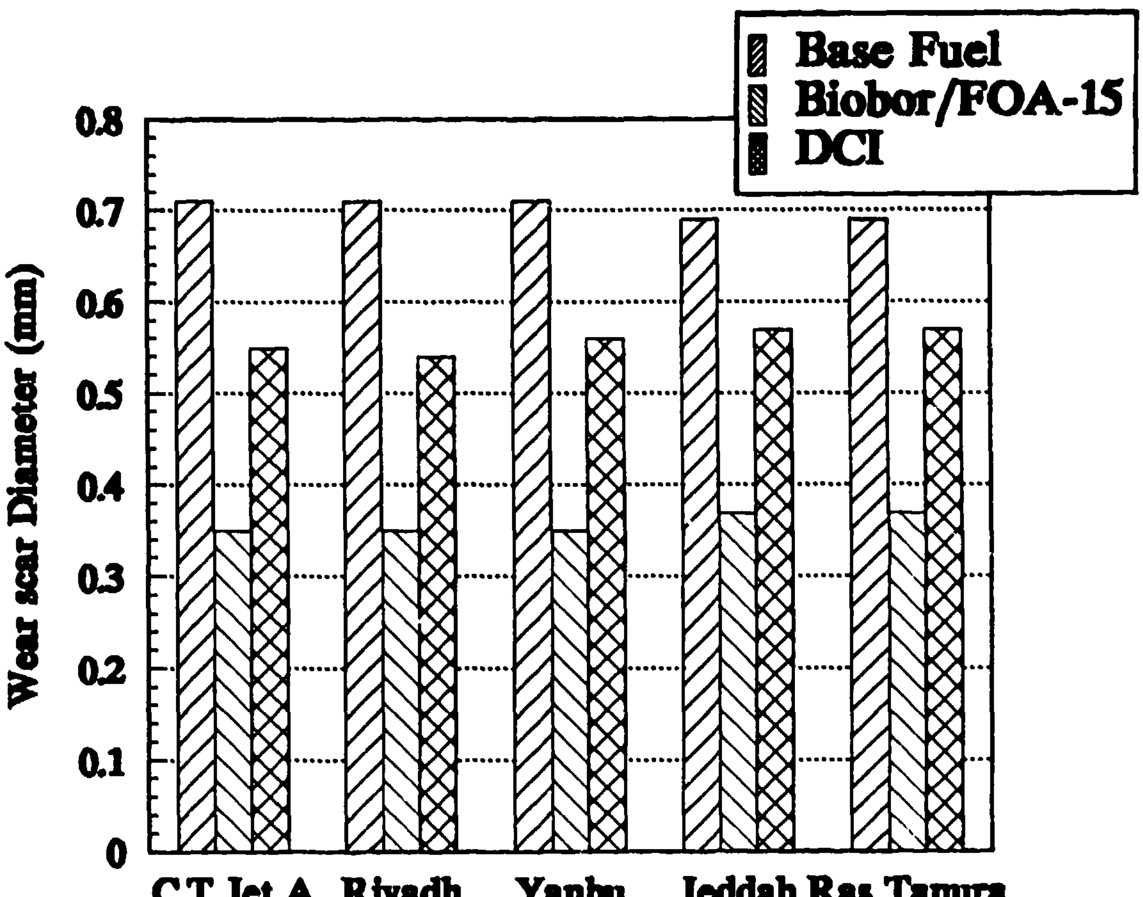


Figure 7. BOCLE wear test results for DCI-4A (15 mg/L) and BIOBOR-JF/FOA-15 (227/71 mg/L) in Saudi Arabian Jet A-1 fuels

fuels were not clay-treated before testing. However, the relatively large wear scar obtained in each instance indicates that the fuels have inherently poor lubricity. The test results obtained with the clay-treated fuel discussed in previous sections are also included for comparison. Clearly, both additives are effective in reducing wear with the range of fuels tested.

5. Effect of Additive Blending

Lubricity additives when blended together may react synergistically, as seen with the BIOBOR-JF/FOA-15 combination. However, additive interference may also occur. No interference is expected when Jet A-1 containing BIOBOR-JF/FOA-15 is added to fuel tanks containing diesel, as MIL-S-53021 is specified primarily for use in diesel fuels.(35)

JP-8 contains a corrosion inhibitor (DCI-4A or similar) and the effect of blending fuels containing this compound with BIOBOR-JF/FOA-15 is unknown. Standard BOCLE tests were carried out using fractions of each additized fuel, with the results shown in Fig. 8. The wear scar produced in each instance is equivalent to that produced by BIOBOR-JF/FOA-15 alone at that concentration (see Fig. 4). No synergism or antagonism appears to exist.

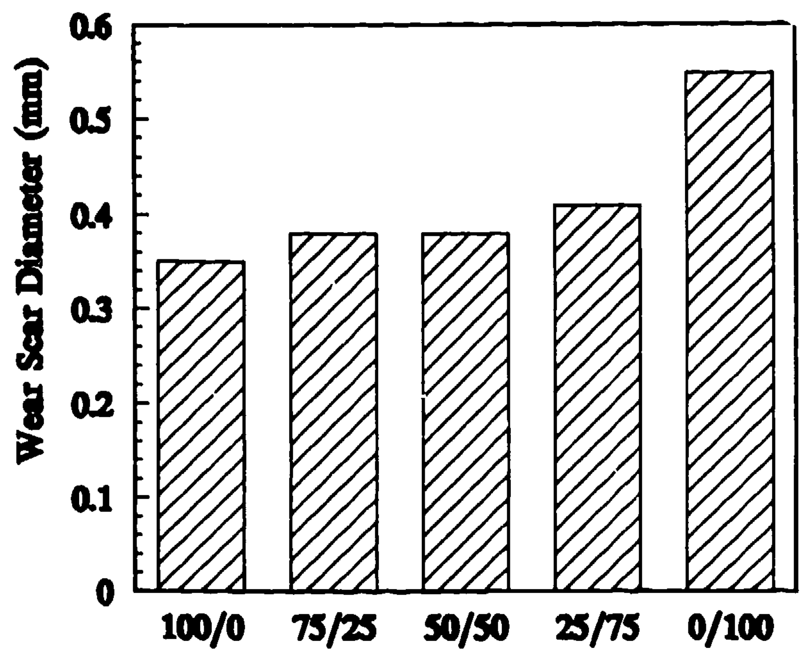


Figure 8. Effects of blending BIOBOR-JF/FOA-15 (227/71 mg/L) with DCI-4A (15 mg/L), each added to clay-treated Jet A-1 at manufacturer's recommended dosage

B. Evaluation of Lubricity Additives Using the Cameron-Plint Apparatus

1. Test Methodology

The previous examination of the more successful lubricity additives was confined to the test materials (AISI E-52100 and SAE 8720 steel) and test conditions defined by the BOCLE test method. These conditions and test materials are not representative of those believed to exist within the Stanadyne rotary fuel injection pump. At the time of testing, no information was available regarding the materials contained in the pumps.

The Cameron-Plint high-frequency wear test apparatus is described in detail in Appendix D and is discussed in Reference 39. In its present configuration, the Cameron-Plint test apparatus is less precise than the BOCLE and has no facilities to aerate the fuel or control humidity and test atmosphere. However, the apparatus has several advantages. In particular, wear testing is possible at normal loads of up to 25 kg with a variety of specimen configurations. This capability allows accelerated wear tests using specimens machined from actual pump components, ensuring the correct metallurgy and hardness.

Wear data from used pumps (summarized in Appendix B) indicate that the drive tang and transfer pump are the most wear-prone areas. As a result, the current test series concentrates on test specimens made from components in these assemblies. To minimize the temperature during machining, the specimens were cut using an electronic discharge machine.

The Cameron-Plint test apparatus produces a reciprocating contact, similar to that believed to exist at the drive tang. The maximum amplitude of the motion between the input shaft and the pump rotor (at the drive tang) was taken to be 0.1 mm. This deviation is likely to occur once per fuel injection cycle, i.e., eight times per pump revolution. The contact pressure at the drive tang was calculated for a torque of 500 inch-pounds. This torque is the maximum required to drive a Stanadyne DB2 pump with a fuel injection pressure of 6000 psi at 2500 rpm and occurs only during the pumping period.(40) The contact area and the average radius of contact between the drive tang and the pump rotor were calculated from measurements of wear scars taken from a selection of used pumps.

The motion between the pump vanes and the eccentric housing is one of unidirectional sliding. The pump vanes are pressed against the eccentric liner by a small spring. Friction between the rotor and the pump vanes adds to the contact load at critical parts of the pump cycle, making precise calculations difficult.

The test conditions and the estimated contact conditions within the pump are provided in TABLE 3, for both the drive tang and pump vanes. In each instance, the figures are an approximation, i.e., the contact pressure varies during each wear test as the size of the wear scar increases. It should be noted that the true sliding speed of the transfer pump vanes is almost an order of magnitude greater than that possible in the Cameron-Plint test apparatus.

TABLE 3. Test Conditions in the Cameron-Plint Wear Apparatus

	Component			
	Pump Vane		Drive Tang	
Parameter	Test	Actual	Test	Actual
Stroke, mm	2.38	-	2.38	~0.1
Frequency, Hz	35	-	5	120 to 240
Speed, mm/s	166	1300 to 2600	23.8	12 to 24
Contact Press, mPa	70	>35	160	190

The tests were carried out at 41°C over a period of 130 minutes. It is likely that the fuel temperature within an operating pump would be considerably in excess of this value. However, higher test temperatures would drive off the lighter fractions of the fuel in an unpressurized environment. In an attempt to produce a slightly higher localized contact temperature, each of the tests was carried out with a short stroke length of 2.38 mm. The effective temperature of the materials in the immediate vicinity of the contact is unknown.

2. Results From Cameron-Plint Tests Using Standard Pump Components

Results from wear tests carried out on the components taken from the transfer pump and drive tang are plotted in Figs. 9 and 10, respectively. Results obtained for the same fuels using the standard BOCLE test per ASTM D 5001 are also included for comparison. The test accuracy achieved with the Cameron-Plint test apparatus was lower than that of the BOCLE. The decrease in repeatability is largely due to difficulty in aligning the test specimens and in measuring the wear scar diameter formed on the pump parts. To improve repeatability, each test was repeated twice and a mean value calculated. The plotted results are expected to be correct within 10 to 15 percent.

Direct quantitative comparison between the Cameron-Plint test results and those from the BOCLE is not possible. Nonetheless, qualitatively good correlation is observed between the BOCLE test results and those of the Cameron-Plint tests, for the relatively lightly loaded transfer pump components. The wear scar diameter caused by Jet A-1 is significantly reduced by the use of lubricity additives. BIOBOR-JF/FOA-15 is particularly effective and produces less wear than Reference No. 2 diesel fuel (Cat 1-H). In addition, a finite contact resistance was measured after approximately 10 minutes of sliding, indicating the presence of a boundary film. No measurable resistance was observed with any of the remaining fuel additives or Cat 1-H diesel. Additional tests were carried out with the four Saudi Jet A-1 fuels available in the theater. Since the results obtained for these tests are similar to the clay-treated fuels, they are not discussed in this report.

The correlation achieved between the Cameron-Plint and the BOCLE tests was relatively poor for the more highly loaded drive tang parts. The lubricity additives still produce a measurable decrease in wear; however, the BIOBOR-JF/FOA-15 combination now produces similar results to DCI-4A. Under these severe contact conditions, diesel is the most effective lubricant.

The friction coefficient measured with the neat Jet A-1 fuel as well as the additive combinations was relatively high and erratic as shown in Fig. 11. The high friction coefficient in the heavily loaded contact indicates that some scuffing may be occurring with Jet A-1. By comparison, the friction coefficient measured during tests lubricated with Cat 1-H was lower and remained steady.

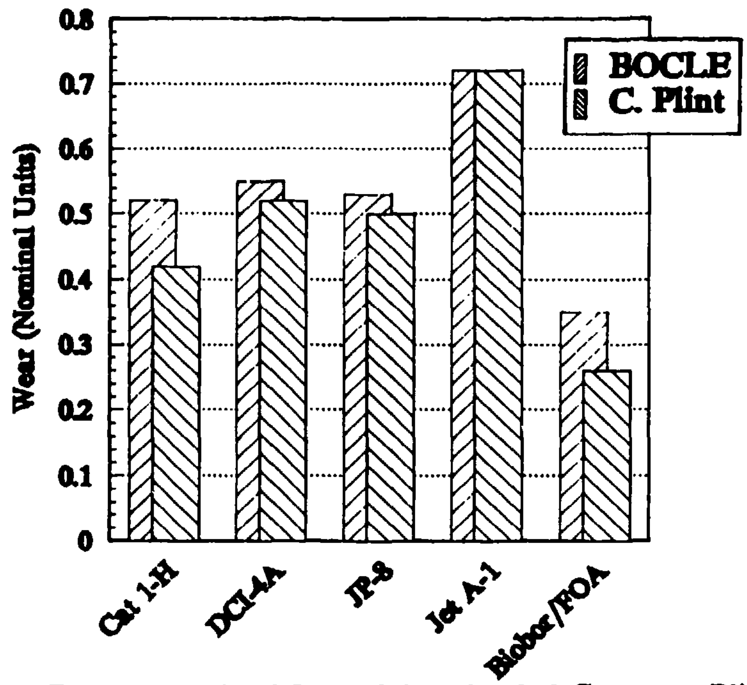


Figure 9. Results obtained from lightly loaded Cameron-Plint tests on specimens cut from the transfer pump

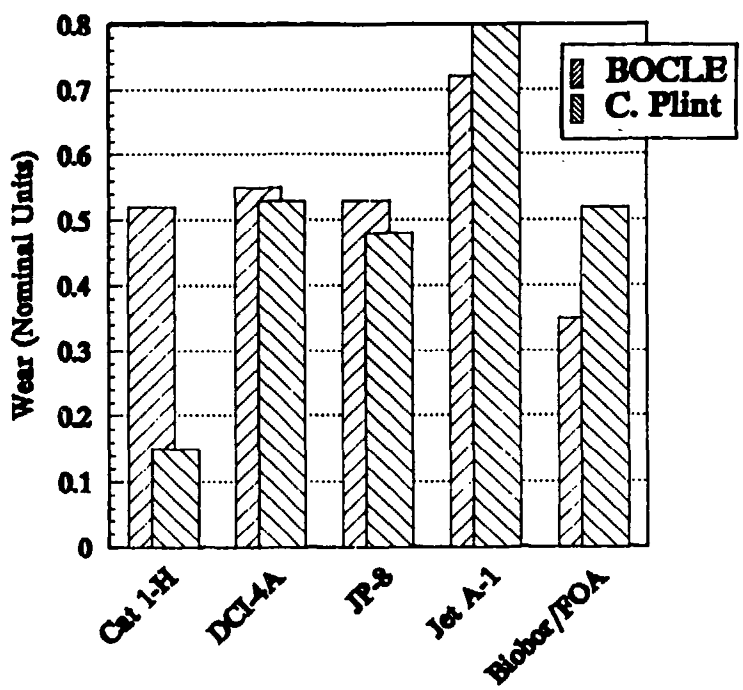


Figure 10. Results obtained from highly loaded Cameron-Plint tests on components cut from the drive tang

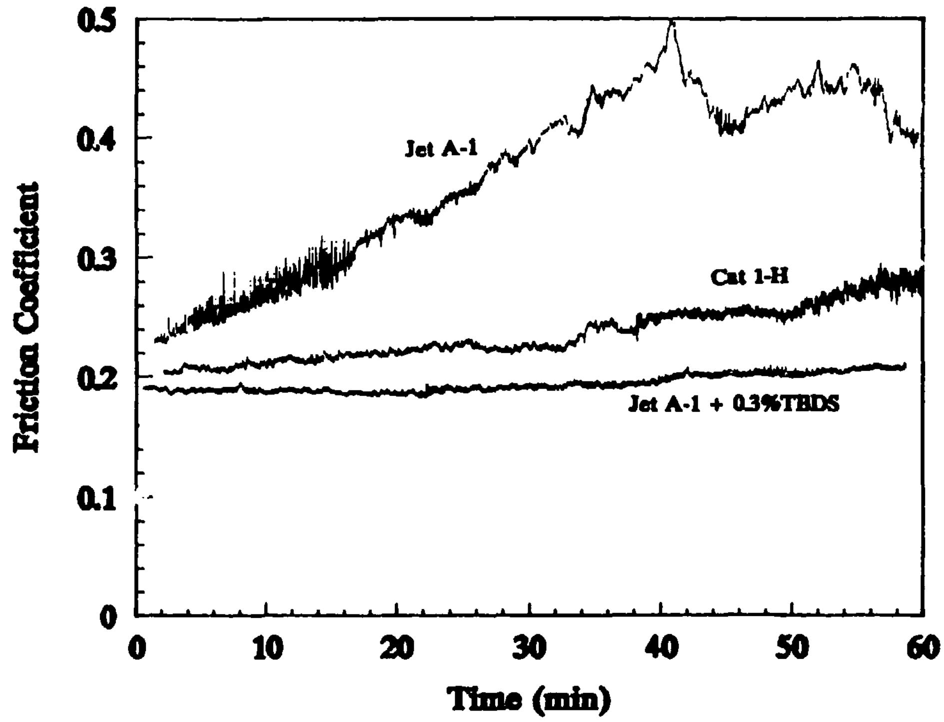


Figure 11. Typical examples of friction coefficient produced by highly loaded pump materials in the Cameron-Plint test apparatus

Addition of 0.3 percent sulfur [di-*tert*-butyl disulfide] to the clay-treated Jet A-1 (<0.002 wt% S) appreciably reduced the measured friction coefficient. A concomitant increase in wear rate was also observed, probably due to a corrosive mechanism. However, an optimum level may exist at which some scuffing load protection is provided with less associated wear.

3. Effect of Dust Particles on Wear Rate

As discussed in Reference 41, a number of workers have described the detrimental effects of sand dust on engine wear. To study this effect in more detail, specimens of "typical" roadside dust from Saudi Arabia were obtained. These dust particles ranged in size from 50 to 200 μm. Cameron-Plint wear tests lubricated with Cat 1-H contaminated with 1 percent Saudi dust were performed. Specimens cut from the transfer pump vanes were used in these tests as it was felt that the relatively soft sintered material would be most vulnerable to two- or three-body abrasion.

Surprisingly, the dust particles had no measurable effect on wear. Despite its fine size distribution, much of the dust settled to the bottom of the fuel reservoir and so probably did not enter the contact area during the test. The tests were repeated with periodic agitation of the fuel bath. However, wear scars similar to the previous tests were recorded.

4. Arctic Pump Vanes

A series of wear tests using the upgraded "arctic" transfer pump vanes and liner were carried out at the same conditions as those detailed for the standard parts in the previous section. The arctic parts were appreciably more wear resistant than the standard parts. As a result, the wear scar produced on the curved surface of the vanes was not significantly greater than the Hertzian diameter due to elastic deformation.

In order to gain a more accurate comparison between the wear rates associated with the standard and arctic parts, a Tallysurf profilemeter was used to accurately measure the wear scar formed on the flat. Profiles were taken across the wear scar produced during each test and the volume of material removed calculated from unfiltered traces. The results are plotted in Fig. 12.

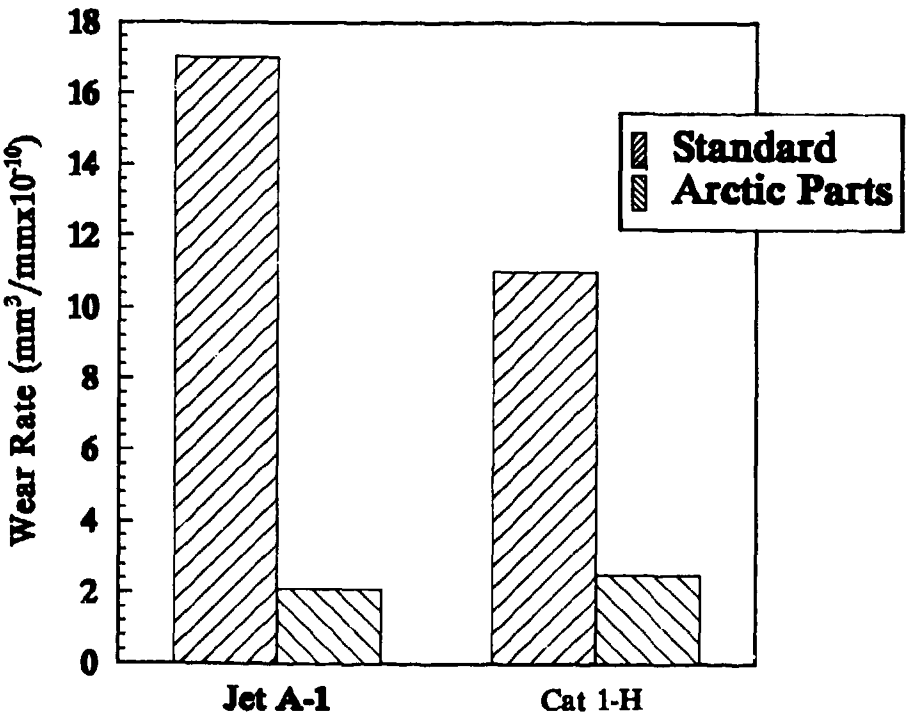


Figure 12. Comparison of the wear rate measured on "arctic" and standard transfer pump components in the Cameron-Plint test apparatus

C. Wear Maps

1. Background

The wear-mapping technique allows representation of wear rate as a function of two simultaneous variables. Clearly, however, many variables play an integral role in wear and, as such, the wear mapping procedure must represent more than a simple plotting technique between two independent variables. It must represent a self-consistent and unified test methodology in which the remaining effects are either accurately defined or eliminated.

The current wear-mapping technique is a development of the work performed at the National Institute of Standards and Technology (NIST) for the study of ceramic materials.(42-43) The NIST study was carried out using a four-ball wear test instrument and a constant duration, step-loading technique. This technique minimized the number of specimens required, while producing a reasonable test rate to create the large volume of data required for each map.

2. Wear Map Test Methodology

Data for the present study were generated using the Cameron-Plint high-frequency reciprocating wear test. In this test, the upper (reciprocating) specimen is a chrome alloy steel ball manufactured from AISI standard steel No. E-52100, with a diameter of 6.35 mm, grade 25 EP finish. This material corresponds with that used in the 12.7-mm diameter ball in the standard BOCLE test. The opposing flat specimen is also AISI standard steel No. E-52100, polished to a mirror finish.

Each wear test was carried out over a constant sliding **distance**, instead of the more usual constant sliding **duration**. This methodology ensures that tests carried out over a range of sliding speeds are directly comparable (simply dividing by the effective sliding distance takes no account of the low-contact pressures formed beneath highly worn specimens).

A short duration test was required to minimize the test time, while still producing a measurable wear scar. To determine the most effective sliding distance, a series of exploratory tests were carried out to define the running-in process for the contact. The tests were carried out at a constant oscillating frequency of 25 Hz, which represents the mean of the speed range available. The test was halted at regular intervals, and the wear scar diameter remeasured **without removing the specimens.** The test could then be restarted without altering the preexisting contact geometry. The wear rate is represented by the diameter of the scar formed on the ball, measured using optical microscopy. If the scar is not circular, an average diameter is calculated from measurements taken along the major and minor axis of the ellipse formed.

Applied loads of 10, 75, and 150 N were used with Cat 1-H diesel and clay-treated (CT) Jet A-1 representing good and bad lubricity fuel, respectively. However, seizure was found to occur with CT Jet A-1 at 150 N. The results obtained at the remaining loads are presented in Fig. 13. For the fuel and load combinations studied, a sliding distance of approximately 150 meters corresponds to the decrease in wear rate after the initial running-in period. This point

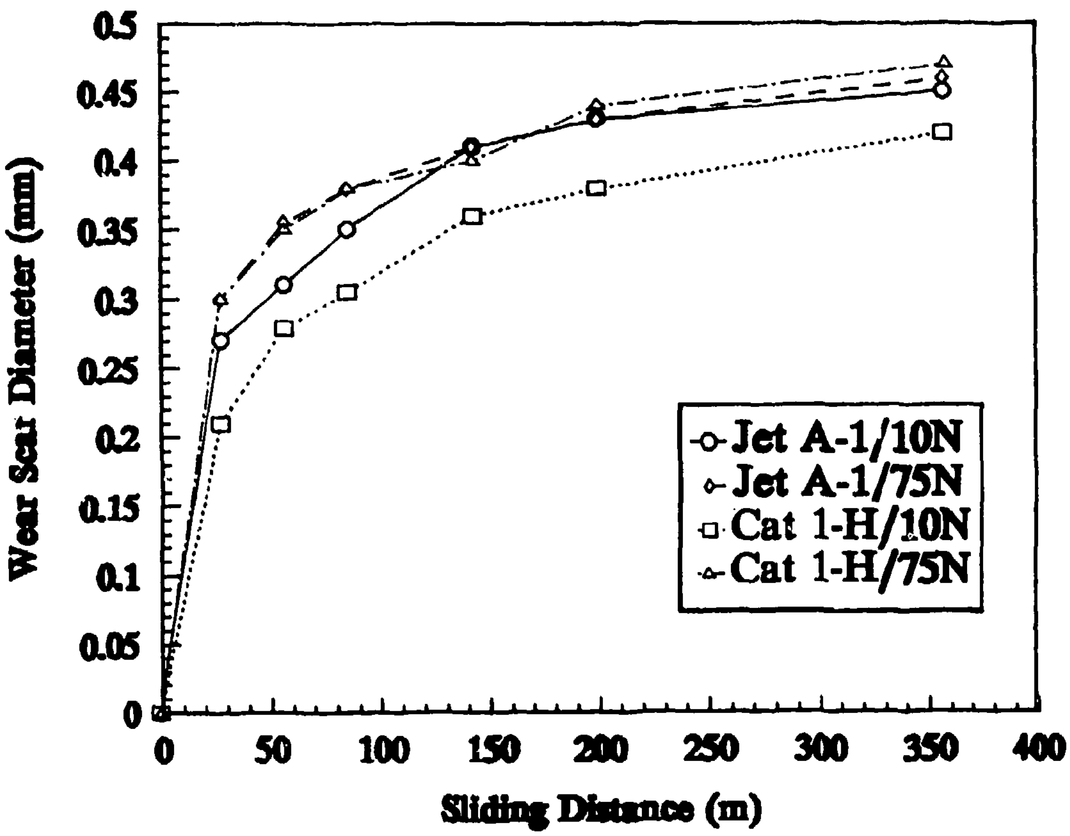


Figure 13. Running-in curves for 52100 steel in Cameron-Plint wear tests

represents the optimum compromise between test duration and wear scar diameter. All subsequent wear tests used in the construction of the wear maps were carried out at this sliding distance.

The test series was carried out at conditions between 30 and 250 mm/s and 10 to 250 N load, representing the full range available on the Cameron-Plint test apparatus. As in previous tests, the test temperature was 41°C. Both friction coefficient and contact resistance were recorded by an y-t plotter throughout each test. The results are left in the form of the measured wear scar diameter, as this is the standard reporting procedure for the BOCLE. **Direct quantitative comparison between the Cameron-Plint apparatus and the BOCLE test results is not possible, due to the differences in test geometry.** However, qualitative comparison between the two test techniques is easier with the data in this form. The volume of material (V) corresponding to a flat of a given diameter (D) on a sphere of radius (R) may be approximately calculated (43) using the following equation:

$$V = (PI \times D^4)/(64R) \qquad \text{(Eq. 1)}$$

The diameter of the ball used in the Cameron-Plint tests is 6.35 mm, compared to 12.7 mm in the BOCLE. The sliding speed in the BOCLE is approximately 615 mm/s at an applied load of [illegible] N.

The wear maps are plotted as a function of applied load and sliding speed. The approximate pressure over the apparent contact area at the end of the test may be calculated from the wear scar diameter, assuming a circular scar. Apparent contact pressure was not used when plotting the results (in place of applied load), as it is not necessarily an accurate representation of the contact pressure during the test. A highly loaded contact will produce a large wear scar, resulting in a comparatively low apparent contact pressure when measured at conclusion of the test.

3. Wear Map Results

Fig. 14 shows the wear map produced by clay-treated Jet A-1 fuel. Two distinct regions are visible in the map, separated by a sharp transition. The lower region represents a wear scar diameter of approximately 0.4 mm and is almost independent of speed and load. An increase in sliding speed produces a slight (but repeatable) decrease in wear at approximately 75 mm/s. The decrease in wear rate is not believed to be due to hydrodynamic lift at higher speeds, as the wear map for diesel (which is a more viscous fuel) is almost independent of sliding speed. Grabel (18) suggests that localized high flash temperatures may cause thermal and oxidative breakdown of normally nonreactive components in the fuel. These reactive components may then be adsorbed on the surface, preventing the formation of an oxide layer.

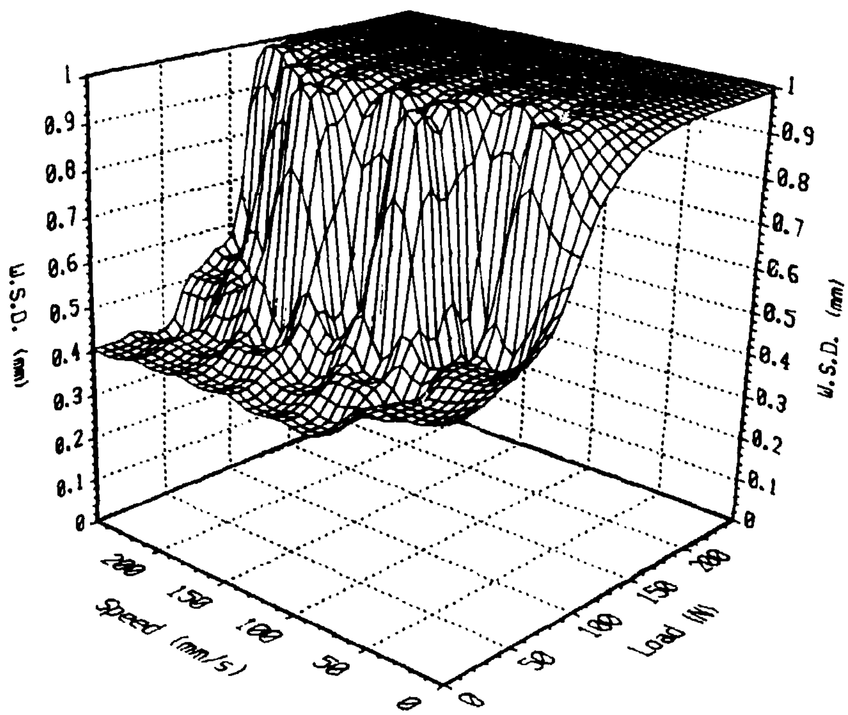


Figure 14. Wear map for 52100 steel lubricated with clay-treated Jet A-1

Transition from low to high wear occurred due to gross scuffing and seizure between the specimens. Higher loads (and, to a lesser extent, speed) caused failure of the weak boundary/oxide layer formed by the fuel. Subsequent metal-to-metal contact between the opposing surfaces caused severe adhesive wear and high friction, halting the test. **When seizure forced premature termination of the test, the wear scar diameter was arbitrarily set to 1.**

The addition of BIOBOR-JF/FOA-15 (MIL-S-53021) to the clay-treated Jet A-1 produces a large drop in wear scar diameter at low loads, as shown in Fig. 15. It should be recalled that according to Eq. 1, wear rate is proportional to wear scar diameter to the power of 4, representing a very significant reduction in wear. However, an increase in applied load produces a concomitant rise in wear, to a level similar to that observed with neat Jet A-1 fuel. As in previous tests, a strong contact resistance was observed with the BIOBOR-JF/FOA-15 additive. No boundary film was observed for the remaining fuels in the tests with 52100 steel.

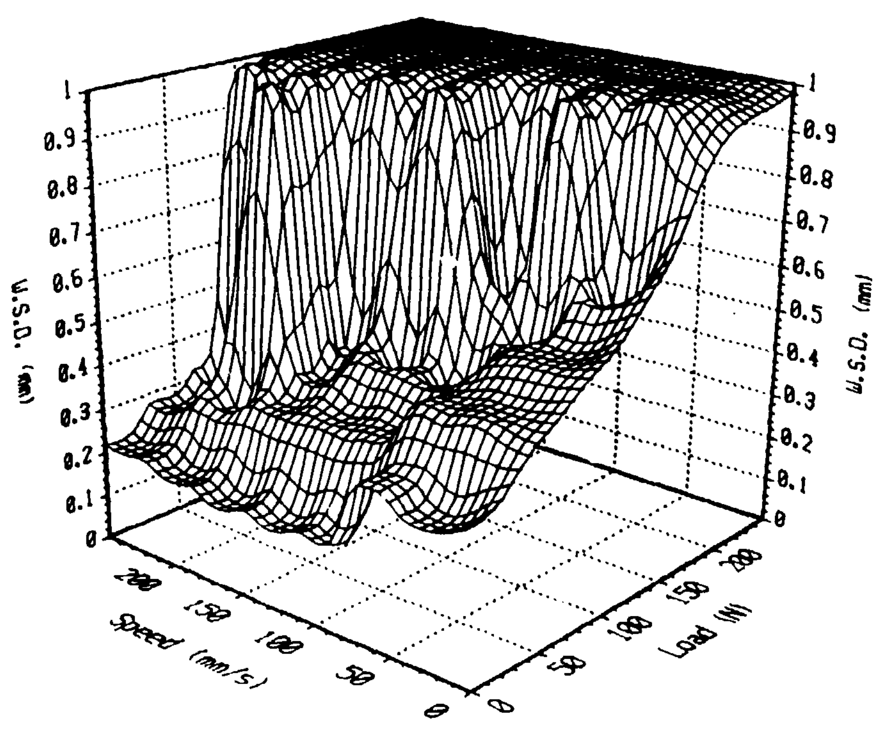


Figure 15. Wear map for 52100 steel lubricated with BIOBOR-JF/FOA-15 at 227 and 71 mg/L, respectively, in clay-treated Jet A-1

The addition of DCI-4A to Jet A-1 also decreases wear (Fig. 16), but to a much lesser extent than the BIOBOR-JF/FOA-15 combination. Both DCI-4A and BIOBOR-JF/FOA-15 appear to delay the onset of seizure by a small amount, particularly at low speeds.

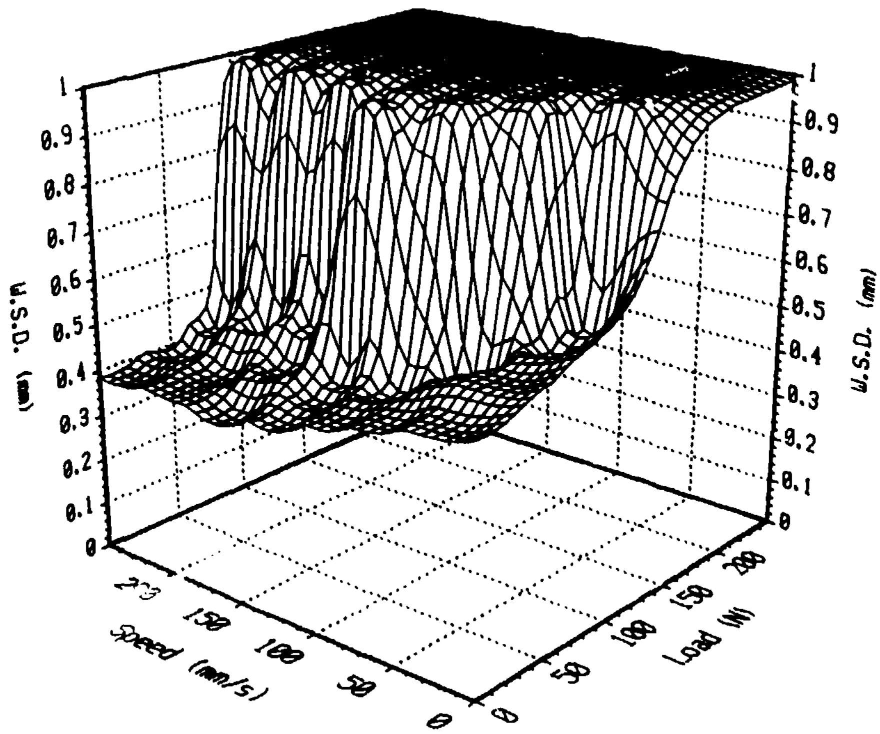


Figure 16. **Wear map for 52100 steel lubricated with 15 ppm DuPont DCI-4A additive in clay-treated Jet A-1**

Fig. 17 shows the wear map constructed for Cat 1-H diesel. At low loads, this fuel produces an intermediate wear rate: lower than clay-treated Jet A-1 but much greater than Jet A-1 with BIOBOR-JF/FOA-15 added. The ranking achieved between the fuels at low loads is similar to that predicted by the BOCLE, as shown in Fig. 18. The wear map data plotted represents test results at a 10-N applied load and 250-mm/s sliding speed. As previously stated, the standard BOCLE conditions are also 10 N (with a 12.5-mm diameter ball) and 615 mm/s.

However, at higher loads, diesel is appreciably more effective than clay-treated Jet A-1 either with or without additives. The increased lubricity of diesel fuels at higher loads was not predicted by the standard BOCLE wear test.

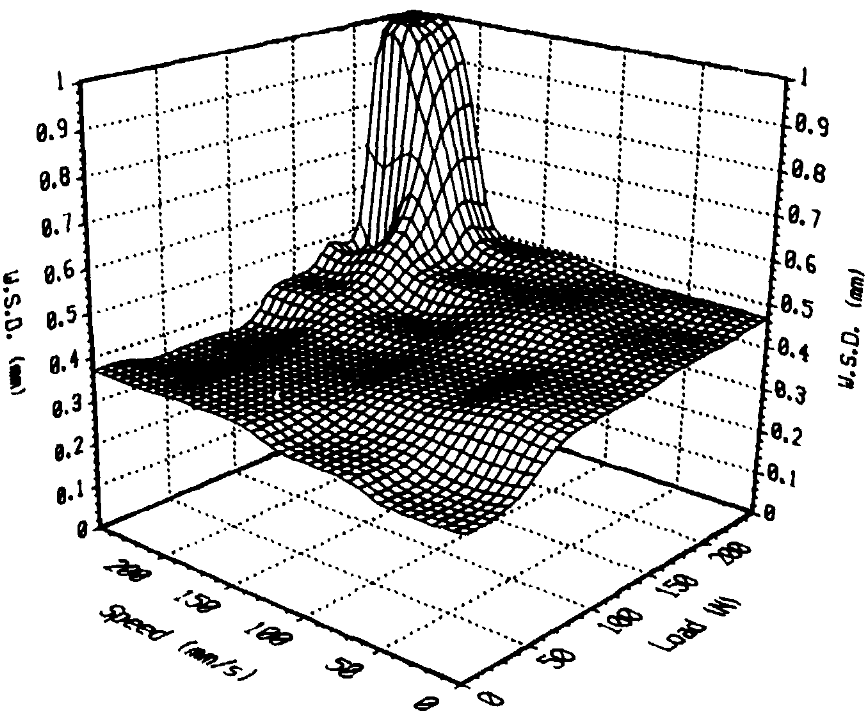


Figure 17. Wear map for 52100 steel lubricated with Reference No. 2 diesel fuel

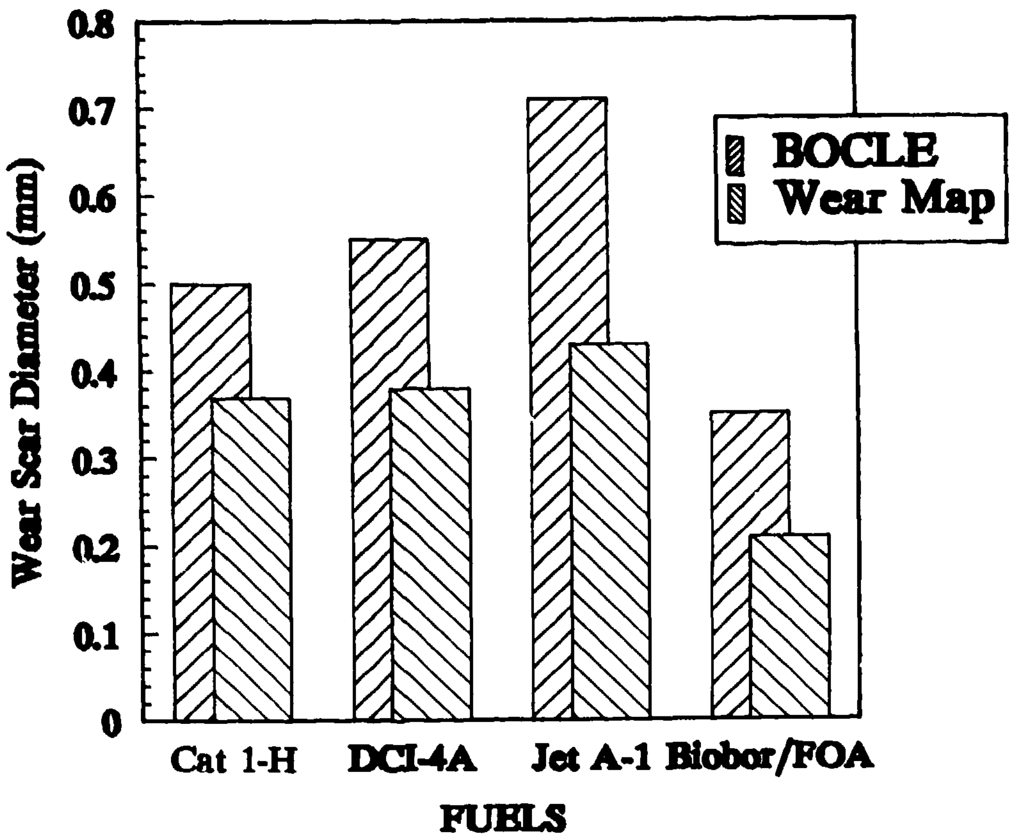


Figure 18. Qualitative comparison between BOCLE test data and data from a lightly loaded region of the wear maps

D. The BOCLE Scuffing Load Test

1. Test Methodology

Hadley and Blackhurst (45) developed a test to predict the scuffing limited performance of fuels. This work also concluded that the standard BOCLE wear test does not provide a unique description of scuffing tendencies for jet fuels. A modified technique was developed to ensure that the BOCLE operated in the scuffing mode. Good agreement was achieved between the modified BOCLE procedure and the results provided by other test rigs such as the Thornton Aviation Fuel Lubricity Evaluator, commonly known as TAFLE.

The modified BOCLE technique differs from the ASTM standard as described in TABLE 4.

TABLE 4. Summary of Modifications to the BOCLE Technique Required for Examination of Scuffing Load

Parameter	Modified BOCLE Technique	Standard ASTM Technique
Duration	60 sec	30 min
Atmosphere	Nitrogen	Air
Loading Mechanism	Motorized	Pneumatic
Conditioning	15 min in nitrogen	15 min in air
Load	1 to 3.5 kg	1 kg

In the revised methodology, a series of 1-minute duration tests was carried out, each with a finite load increment. A new ball is used for each test. At a critical load, scuffing wear should occur, reflected by an increase in wear scar diameter at that point. The procedure recommends that the tests be run in nitrogen in order to restrict access of oxygen to the contact. The fuel reservoir must be conditioned with nitrogen for 30 minutes before each test to remove all traces of oxygen. Oxygen promotes thermal degradation of the fuel (45), to form lubricous products. Such degradation may be less likely to occur in a fully flooded contact. However, it should be recognized that friction polymers are commonly observed in both flooded and open contacts.

2. BOCLE Scuffing Load Test Results

A number of modified BOCLE tests were carried out using Jet A-1 and Cat 1-H diesel fuel. A selection of these results is shown in Fig. 19. A relatively weak transition was observed in each instance, spanning approximately 0.75 kg of loading. The exact point at which transition may be said to occur requires a subjective judgment on the part of the operator. In addition, the repeatability of the tests was relatively poor, particularly around the critical transition region.

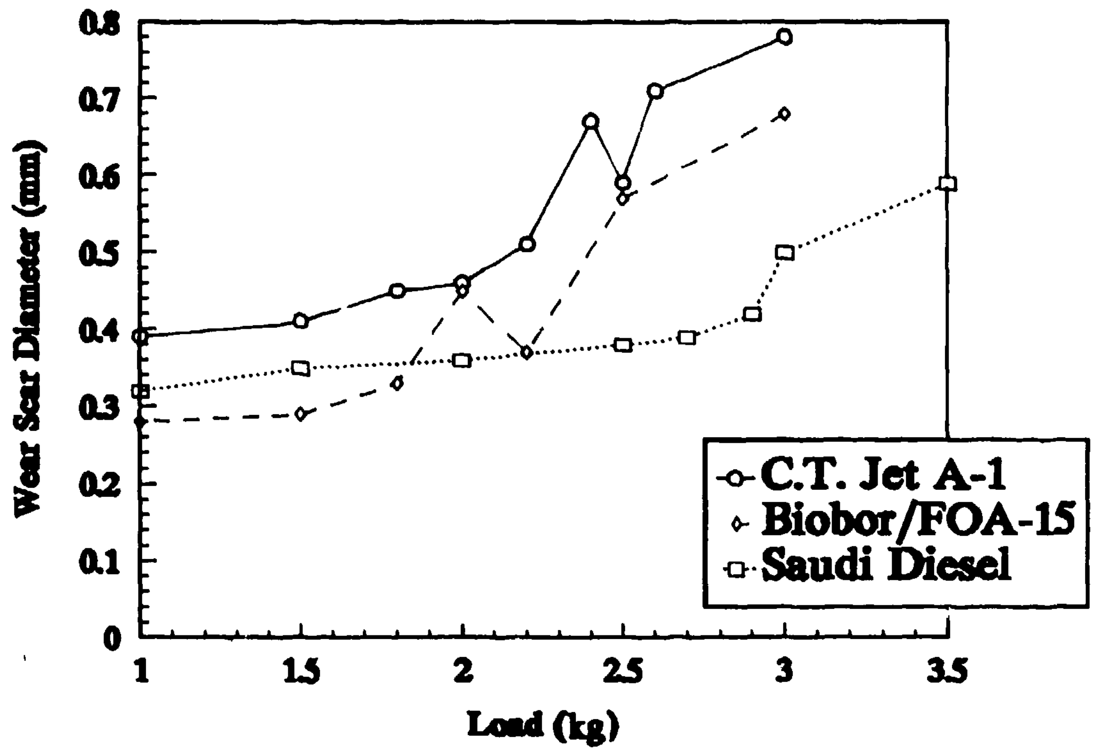


Figure 19. Results of scuffing load tests using modified BOCLE procedure

The BOCLE apparatus used in the current work was equipped with a friction force measurement arm. Examination of the friction traces produced indicates that for tests within the transition region, the coefficient of friction varies dramatically as a function of time. At the start of the test, relatively high friction is seen, decreasing to a constant value of approximately 0.1 at the end of the 1-minute test. The amount of time required for the friction coefficient to decrease was a function of test load. The high friction value probably corresponds to scuffing and severe adhesive wear, while 0.1 is approximately the value observed during long duration tests, i.e., produced by mild oxidative wear.

The initial contact between the counterformal test specimens produces a relatively high Hertzian contact loading of 930 N/mm^2. Previous studies of the running-in process for the BOCLE (46) indicate that a rapid decrease in pressure occurs immediately after beginning the test. After 2 minutes, the apparent contact pressure is only 80 N/mm^2. The decrease in contact pressure allows rapid recovery from severe wear and scuffing to mild oxidative wear and corrosion. The ability of the contact to recover from the scuffing wear mechanism at a critical period in the test process makes interpretation of the test results considerably more difficult.

An alternative technique is currently being developed in which the applied load is rapidly and continuously increased. The initial test results indicate that this loading mechanism prevents recovery from severe scuffing to mild corrosive wear.

VI. SUMMARY AND CONCLUSIONS

A. Summary

It has been shown that relatively severe oxidative wear occurs with low-lubricity fuels such as Jet A-1. Corrosion inhibitors such as DCI-4A are particularly effective in reducing this type of wear. As an immediate response to the failure of rotary fuel injection pump failures operated with Jet A-1 fuel, a range of possible fuel lubricity additives was evaluated. The standard BOCLE test as defined by ASTM D 5001 indicated that BIOBOR-JF/FOA-15 was the most effective additive. However, the wide range of interrelated parameters involved makes accurate representation of a fluid's lubricating capacity in a single test almost impossible. A series of nonstandard BOCLE tests tended to confirm the initial result.

The Cameron-Plint wear apparatus was used in an attempt to simulate the wear mechanisms and metallurgical properties found in the Stanadyne rotary fuel injection pump. For lightly loaded components, good correlation was achieved between the Cameron-Plint test results and those results previously obtained from the BOCLE. Under more severe conditions, a different ranking among the fuels emerged.

An in-depth parametric study of fuel lubricity was undertaken using a wear-mapping technique. The results from this study indicate that the onset of scuffing wear and seizure does not appear to be reflected in the wear rate under more lightly loaded conditions. This is in general agreement with some previous work (45) in the same area.

The ultimate load requirements of fuel injection pumps are currently undefined. Clearly, any seized pump has suffered gross failure of the boundary film between the opposing surfaces. In many instances, however, the seizure is a secondary problem promoted by a malfunction in another area of the pump. Often the primary cause of failure also appears to be wear related. None of the pumps seen at BFLRF had evidence of severe scuffing, rather the highly worn surfaces were polished in appearance. This polished appearance would indicate a relatively mild corrosive wear mechanism, well represented by the standard BOCLE wear test method.

However, the manufacturer believes that scuffing is a pertinent mechanism and has provided some scuffed transfer pump components to BFLRF. In addition, simple wear tests designed to simulate pump operation indicate that critical components are relatively highly loaded and close to failure of the boundary layer. If this is the case, a bench test capable of defining the scuffing load resistance of fuels is required.

B. Conclusions

The following conclusions have been reached as a result of this study:

1. The use of low-lubricity fuels will certainly promote increased wear of Stanadyne Rotary Fuel injection pumps.

2. The low viscosity of Jet A-1 fuel compared to diesel (DF-2) should not cause failure of the hydrodynamic film around the pump rotor under normal operating conditions.

3. A definite need exists for a bench test that represents the lubr city requirements of fuel injection equipment.

4. Examination of highly worn fuel pump components indicates that the primary material removal mechanism is likely to be oxidative/corrosive wear.

5. BIOBOR-JF/FOA-15 was the most effective lubricity additive studied. It significantly decreased oxidative wear at low loads, but had little effect in more highly loaded contacts prone to scuffing. No other additive qualified under MIL-S-53021 was effective in improving fuel lubricity.

6. Most corrosion inhibitors (MIL-I-25017) are also effective (and widely recognized) lubricity additives, and these decrease the wear rate in lightly loaded contacts to a level similar to that seen with diesel.

7. The standard BOCLE wear test as delineated by ASTM D 5001 is a highly representative and accurate test of fuel/additive lubricity for lightly loaded contacts.

8. The results predicted by the standard BOCLE wear test do not reflect the ability of fuels to lubricate in more highly loaded contacts prone to scuffing.

9. The Cameron-Plint apparatus is capable of assessing fuel lubricity at low loads and may also be used to define the scuffing load point. In its present form, the Cameron-Plint apparatus is a less well-controlled wear test than the BOCLE.

10. A modified BOCLE wear procedure was identified that may have the potential to predict the ability of a fuel to resist scuffing wear.

11. Upgraded ("arctic") transfer pump components available as the arctic conversion kit for the Stanadyne DB2 pump had appreciably lower wear rates than the standard parts.

12. A significant difference in lubricity generally exists between JP-8 and Jet A-1. The two should not be considered to have identical or similar lubricity properties.

13. The lubricity requirements/failure mechanisms of fuel injection equipment require further definition.

VII. ADDITIONAL WORK

1. A series of pump tests are to be carried out using both arctic and standard pumps, lubricated with both neat and additized fuels.

2. The results obtained from the pump stand test tests will be used to define the fuel lubricity requirements of the Stanadyne pump.

3. The modified BOCLE technique to determine the scuffing load capabilities of fuels will be further developed.

4. An attempt will be made to find a correlation between the needs of the Stanadyne rotary fuel injection pump and a wear test.

5. The operation of BIOBOR-JF/FOA-15 as a boundary additive will be studied in more detail.

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ABBREVIATIONS AND ACRONYMS

AFLRL	- U.S. Army Fuels and Lubricants Research Laboratory
AISI	- American Iron and Steel Institute
ASTM	- American Society for Testing and Materials
Belvoir RDE Center	- U.S. Army Belvoir Research, Development and Engineering Center
BFLRF	- Belvoir Fuels and Lubricants Research Facility
BOCLE	- Ball-on-Cylinder Lubricity Evaluator
CT	- Clay Treated
CUCV	- Commercial Utility Cargo Vehicles
DF-2	- No. 2 Diesel Fuel
DOD	- Department of Defense
NATO	- North Atlantic Treaty Organization
NIST	- National Institute of Standards and Technology
S	- Sulfur
SAE	- Society of Automotive Engineers
SwRI	- Southwest Research Institute
TAFLE	- Thornton Aviation Fuel Lubricity Evaluator
TBDS	- di-*tert*-butyl disulfide

APPENDIX A

Pump Rig Tests

A number of pump tests were carried out to quantify the effects of increased side loading on pump operation. These tests were performed on standard Stanadyne DB2 rotary fuel injection pumps. The unitest pump stand and test equipment specification are described in more detail in the report by Montemayor and Owens*. A schematic diagram of the fuel line system is shown in Fig. A-1 below.

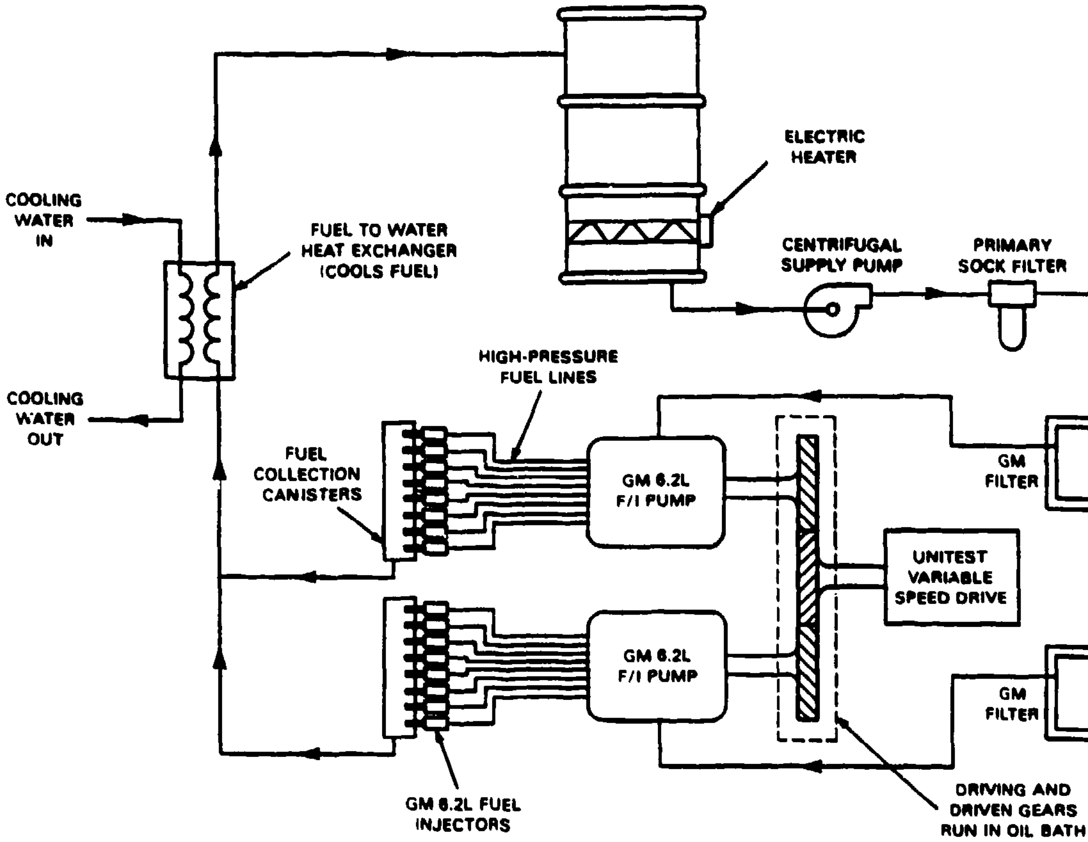

Figure A-1. <u>Schematic diagram of the fuel system used in pump tests</u>

Artificially high side loading on the pump rotor was created by obstructing the passage to the pressure regulator in the transfer pump. The high transfer pump pressure produced a high sideloading on the rotor, away from the fuel outlet port. The transfer pump pressure produced was continuously monitored during operation.

* Montemayor, A.F. and Owens, E.C., "Comparison of 6.2L Arctic and Standard Fuel Injection Pumps Using JP-8 Fuel," Interim Report BFLRF No. 218 (AD A175597), prepared by Belvoir Fuels and Lubricants Research Facility, Southwest Research Institute, San Antonio, TX, October 1986.

Initial tests at a fuel inlet temperature of 41°C and a rotor speed of 1960 rpm, produced a transfer pump pressure in excess of 300 psi. Subsequent tests were carried out at a fuel inlet temperature of 95°C, producing a transfer pump pressure of 230 psi. The above test sequence was carried out with three pumps, all of which operated normally after 3 hours at both conditions.

Finally, intermittent tests were carried out to simulate equipment start-up. The pump was rapidly accelerated from rest to 1800 rpm and operated for 10 minutes. This procedure was repeated for 2 hours. Once again, none of the three pumps failed during testing.

APPENDIX B

Wear Levels Observed on Used Pump Components

TABLE B-1. Subjective Wear Level* on Used Pump Contents

Component		Pump No. 1	2	3	4	5	6	7
Hydraulic Head & Rotor	Hydraulic Head	5	1	0	1	1	(5-)	(5)
	Discharge Fittings	0	0	0	0	0	(-0-)	(0)
	Distributor Rotor	5	1	0	1	1	(5-)	(5)
	Delivery Valve	3	3	0	1	3	(3)	(2)
	Plungers	1	0	0	0	1	(1)	(1)
	Cam Rollers & Shoes	1	2	1	1	1	(1)	(-0)
	Leaf Spring and Screw	1	1	0	0	0	(1)	(1)
	Cam	0	4	0	0	0	(0)	(0)
	Governor Weight Retainer	1	3	0	0	3	(1)	(0)
	Governor Weights	0	0	0	0	0	(0)	(0)
	Governor Thrust Washer	2	2	0	1	1	(1)	(1)
	Governor Thrust Sleeve	1	1	0	0	0	(0)	(0)
	Drive Shaft Tang						(4)	
Transfer Pump	Inlet Screen	1	4	NA	NA	NA	(Clean)	(0)
	Regulating Adj. Plug	0	4	NA	0	0	(0)	(0)
	Regulating Piston	3	4	NA	1	1	(2)	(1)
	Regulator	4	3	2	2	1	(4)	(2)
	Blades	2	3	1	1	1	(5)	(4)
	Liner	3	3	3	3	2	(4)	(1)
	Rotor Retainers	3	3	1	2	2	(2)	(3)
Governor	Metering Valve	3	4	0	1	1	(1)	(0)
	Metering Valve Arm	1	1	0	0	1	(1)	(0)
Advance	Piston	2	4	0	1	1	(1)	(1)
	Cam Advance Screw	2	2	0	0	0	(2)	(1)
	Plugs	0	2	0	0	0	(0)	(0)

* 0 = no wear; 5 = failure.
( ) = DB2 pumps from HMMWV, GM 6.2L engines; all other are DBM pumps from diesel generator sets.
NA = Parts were not available when pump was received at BFLRF.

Note:
Pump No. 1 = Serial No. 5545723
Pump No. 2 = Serial No. 6192152
Pump No. 3 = Serial No. 5258129
Pump No. 4 = Serial No. 6192153
Pump No. 5 = Serial No. 6192664
Pump No. 6 = Serial No. 6594676
Pump No. 7 = Serial No. 6594864

APPENDIX C

Fuel Properties

TABLE C-1. U.S. Jet A-1 Turbine Fuel
Batch No.: 90-2B Date: November 3, 1990
AL-19546-F

Test	Specifications Minimum	Specifications Maximum	Result
Gravity, °API	37.0	51.0	49.5
Density, kg/m	0.775	0.840	0.782
Color	Report		+25
Distillation, °C			
Initial Boiling Point			160
5%			165
10%		204	167
20%			169
30%			170
40%			172
50%			175
60%			178
70%			182
80%			187
90%			195
95%			207
End Point		300	218
Recovery, vol%			99.1
Residue, vol%		1.5	0.9
Loss, vol%		1.5	0.0
Sulfur, wt%		0.300	0.002
Doctor Test		Neg.	Neg.
Freeze Point, °C		-47.0	-59.5
Flash Point, °C	38		44
Viscosity, cSt, at -34°C		8.0	4.2
Viscosity, cSt, at 40°C			1.07
Copper Corrosion		1B	1B
Existent Gum, mg/100 mL		7.0	3.4
Particulates, mg/L		1.0	0.8
Smoke Point, mm	20.0		29.0
WSIM	Report		99
Hydrocarbon Composition, vol%			
Aromatics		20.0	8.1
Olefins		5.0	0.0
Saturates	Report		91.9
Acidity, total (mg KOH/g)		0.015	0.004
Net Heat of Combusion, Btu/lb	18,400		18721
JFTOT, mm Hg		25.0	0.0
JFTOT, TDR		12	1
Water Reaction		1B	1A
Separation Rating, max.		2.0	0.0
Interfacing Rating, max.		1B	1A

TABLE C-2. Reference No. 2 (Cat 1-H) Diesel Fuel
Batch No.: 90-6 Date: September 26, 1990
AL-19561-F

Test	Specifications Minimum	Specifications Maximum	Result
Gravity, °API	33.0	35.0	34.1
Distillation, °F (°C)			
Initial Boiling Point			400 (204)
5%			449 (232)
10%			462 (239)
20%			476 (247)
30%			489 (254)
40%			501 (261)
50%	500	530	515 (268)
60%			531 (277)
70%			550 (288)
80%			573 (301)
90%	590	620	611 (322)
95%			642 (339)
End Point	650	690	669 (354)
Recovery, vol%			99.0
Residue, vol%			1.0
Loss, vol%			0.0
Cetane Number	47.0	53.0	50.0
Flash Point, °F (°C)	140 (60)		188 (87)
Cloud Point, °F (°C)			24 (-4)
Pour Point, °F (°C)		20 (-7)	15 (-9)
Water and Sediment, vol%		0.05	<0.05
Sulfur, wt%	0.38	0.42	0.39
Ash, wt%		0.010	0.001
Viscosity, cSt, at 40°C	2.00	4.00	3.00
Copper Corrosion		2	1A
Neutralization No., mg KOH/g		0.15	0.07
Ramsbottom, 10% residium, wt%		0.20	0.10

TABLE C-3. Saudi Arabian Jet A-1 Fuels

Test	Test Method	Requirements	Riyadh 08-02-89 Test Results	Jeddah 02-24-90 Test Results	Yanbu 02-25-90 Test Results	Ras Tanura 01-31-90 Test Results
Visual Appearance	Clear, bright, and visually free from solid matter and undissolved water at normal, ambient temperature.		Cl/Br	Cl/Br	Cl/Br	Cl/Br
Total Acidity	ASTM D 3242	0.015, max	0.0024	--	0.023	0.005
Aromatics, vol%	ASTM D 1319	20.0, max†	19.9	--	19.0	19.4
Olefins, vol%	ASTM D 1319	5.0, max	0.5	--	0.3	0
Totai Sulfur, wt%	ASTM D 4294 or ASTM D 1266	0.30, max	0.01	--	0.12	0.09
Mercaptan Sulfur, wt% or	ASTM D 3227	0.003, max	0.0003	--	0.0009	0.0005
Doctor Test	ASTM D 484	Negative	--	--	--	Negative
Mercaptan Sulfur, ppm	UOP 163	30, max	--	--	--	--
Distillation, °C	ASTM D 86 or					
Initial Boiling Point	ASTM D 86 Auto	Report	142	153	152	160
10%	Dist., or ASTM D 2887	204, max	169	170	171	179
20%		Report	175	176	175	184
50%		Report	190	194	186	196
90%		Report	223	231	203	219
End Point		300, max	245	249	229	248
Residue, vol%		1.5, max	1.2	1.0	1.3	1.0
Loss, vol%		1.5, max	0	0	0.7	0

† Recommended, Preliminary (?) means needs discussion.

TABLE C-3. Saudi Arabian Jet A-1 Fuels (Cont'd)

Test	Test Method	Requirements	Riyadh 08-02-89 Test Results	Jeddah 02-24-90 Test Results	Yanbu 02-25-90 Test Results	Ras Tanura 01-31-90 Test Results
Flash Point, °C	ASTM D 56 or ASTM D 56 Auto. Flash Tester	38, min	42	46	47	48
Density at 60°F (15°C), kg/L	ASTM D 1298	0.775 to 0.830	0.7875	0.7875	0.7837	0.7884
API Gravity at 60°F (16°C)	ASTM D 1298	39 - 51	48.16	47.52	49.0	47.9
Freeze Point, °C	ASTM D 2386	-50, max†	-55	-50	-60	-55
Viscosity, -4°F (-20°C), cSt	ASTM D 445	8.0, max	3.49	--	2.73	3.51
Hydrogen Content, mass%	ASTM D 3701	13.9, min	--	--	--	--
Thermal Value, Net Btu/lb (J/g)	ASTM D 2382, 240 or 1405	18,400 (42,800), min	-- --	-- --	-- --	-- 18,583

† Recommended, Preliminary (?) means needs discussion.

TABLE C-4. Saudi Arabian Diesel Fuels

Test	Test Method	Requirements	Riyadh 08-23-89 Test Results	Jeddah 02-18-90 Test Results	Yanbu 02-19-90 Test Results	Ras Tanura 03-10-90 Test Results
Appearance	ASTM D 4176	C & B				
Ash, wt%	ASTM D 482	0.01, max	Trace	0	Nil	0
Carbon Residue, 10% Bottoms, wt%	ASTM D 524	0.20, max	0.08	0.143	0.09	0.07
Cloud Point, °F (°C)	ASTM D 2500					
May - September		+45 (7.2), max	--	--	--	--
October - April		+35 (1.6), max	+1 (-17)	-4 (-20)	+28 (-2)	+24 (-4)
Color	ASTM D 1500	3.0, max	--	--	--	0.25
Copper Strip Corrosion, 3 hours at 212°F (100°C)	ASTM D 130	2, max	1A	1A	1	1A
Diesel Index	IP 21	55, min	--	--	--	--
Distillation, °F (°C)	ASTM D 86 or					
10%	ASTM D 86 Auto.	NR*	417 (214)	399 (204)	--	424 (218)
50%	Dist.	NR	530 (277)	516 (269)	--	532 (278)
85%		662 (350), max	--	--	633 (334)	--
90%		675 (357), max	685 (363)	646 (341)	--	643 (339)
End Point		725 (385), max	730 (388)	714 (379)	702 (372)	677 (358)
Flash Point, °F (°C)	ASTM D 93 or ASTM D 93 Auto. Flash Tester	140 (60), min	158 (70)	153 (67)	158 (70)	164 (73)

TABLE C-4. Saudi Arabian Diesel Fuels (Cont'd)

Test	Test Method	Requirements	Riyadh 08-23-89 Test Results	Jeddah 02-18-90 Test Results	Yanbu 02-19-90 Test Results	Ras Tanura 03-10-90 Test Results
Gravity	ASTM D 1298					
	API	34.0 to 42.0	38.6	38.55	38.1	37.7
	Specific, 60/60°F	0.815 to 0.855	0.8321	0.8321	0.8342	0.8363
Pour Point, °F (°C)	ASTM D 97					
May - September		+35 (1.6), max	--	--	--	--
October - April		+25 (-3.8), max	--	+25 (-3.8)	--	-10 (-23)
Sulfur, wt%	ASTM D 4294 or ASTM D 1266	1.0 max	0.99	0.809	1.0	0.97

APPENDIX D

Cameron-Plint Wear Test Apparatus

Work by Kanakia, Cuellar, Jr., and Lestz used the Cameron-Plint High Frequency Reciprocating Machine to develop fuel wear tests.* The Cameron-Plint wear test apparatus is intended primarily for the rapid assessment of the performance of lubricants and lubricant metal combinations. The apparatus is shown in Fig. D-1. An upper specimen slides on a lower flat with a pure sinusoidal motion. The scotch yoke mechanism that provides this motion is driven by a variable speed motor. The amplitude of the stroke may be varied from 2 to 15 mm, at frequencies ranging from 5 to 50 Hz.

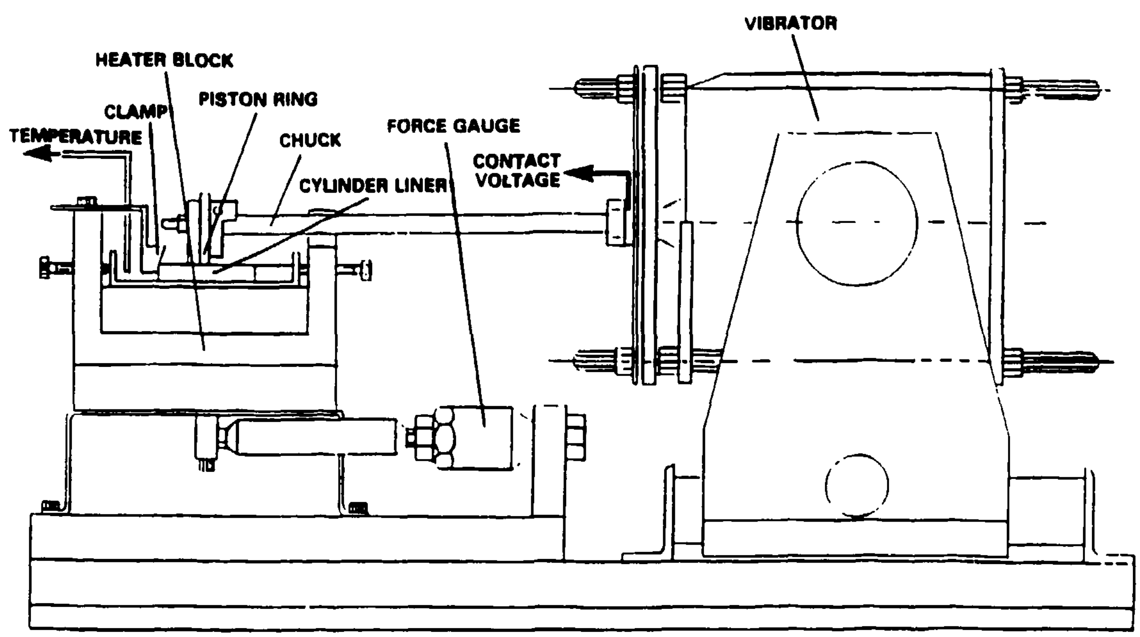

Figure D-1. Schematic diagram of the Cameron-Plint wear test apparatus

The lower (fixed) specimen is carried in a stainless steel bath mounted on a heater block. The upper (oscillating) specimen is loaded using a spring balance. The friction force on the lower specimen is measured by a piezoelectric force transducer, with a resolution of 0.001 N. Electrical output from the transducer is recorded on a y-t chart recorder, independent of sliding direction.

* Kanakia, M.D., Cuellar, J.P., Jr. and Lestz, S.J., "Development of Fuel Wear Tests Using the Cameron-Plint High-Frequency Reciprocating Machine," Interim Report BFLRF No. 262 (AD A216003), prepared by Belvoir Fuels and Lubricants Research Facility, Southwest Research Institute, San Antonio, TX, May 1989.

Electrical Contact Resistance Measurement

A Lunn-Furey circuit (Fig. D-2) was used to measure the contact resistance formed between the sliding specimens. A potential of 20 millivolts is applied across the specimens by a potential divider, and the contact resistance is observed. The voltage drop across the contact is representative of the contact resistance. The output may be recorded on a y-t plotter.

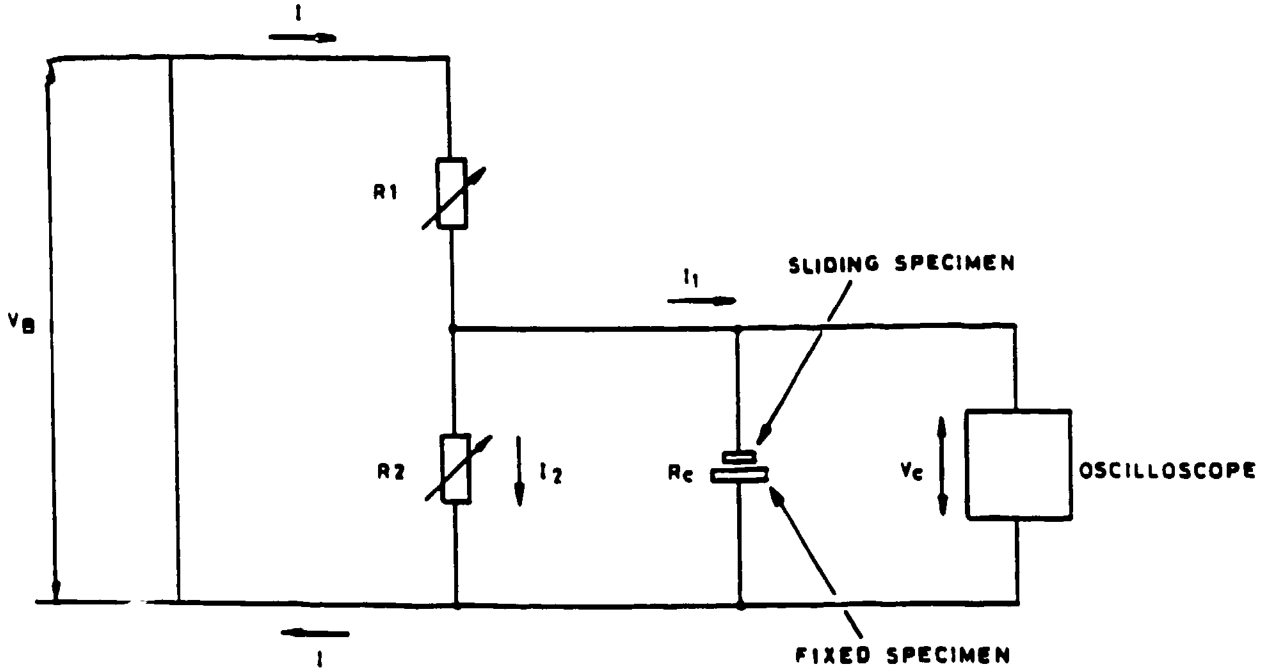

Figure D-2. Lunn-Furey circuit for contact resistance measurement

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