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MIL-L-87177 Lubricant Bulletproofs Connectors Against Chemical and Fretting Corrosion.

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Prepared by
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MIL-L-87177 Lubricant Bulletproofs Connectors Against Chemical and Fretting Corrosion.

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Abstract

Electrical connectors corrode. Even our best SA and MC connectors finished with 50 to 100 microinches of gold over 50 to 100 microinches of nickel corrode. This work started because some, but not all, lots of connectors held in KC stores for a decade had been destroyed by pore corrosion (chemical corrosion). We have identified a MIL-L-87177 lubricant that absolutely stops chemical corrosion on SA connectors, even in the most severe environments. For commercial connectors which typically have thinner plating thicknesses, not only does the lubricant significantly retard effects of chemical corrosion, but also it greatly prolongs the fretting life. This report highlights the initial development history and use of the lubricant at Bell Labs and AT&T, and the Battelle studies and the USAF experience that lead to its deployment to stop dangerous connector corrosion on the F-16. We report the Sandia, HFM&T and Battelle development work, connector qualification, and material compatibility studies that demonstrate its usefulness and safety on JTA and WR systems. We will be applying MIL-L-87177 Connector Lubricant to all new connectors that go into KC stores. We recommend that it be applied to connectors on newly built cables and equipment as well as material that recycles through manufacturing locations from the field.

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Acknowledgements

Thanks go out to Micky Clifford, Ed Fuller, Joe Laoruangroch, Anna Crabtree, Mike Conley, Charlie Cook and Charlie Long at Honeywell. Thank you Brian Geery (SNL-Org 2125) for working with us to collect the spectroscopic data on the UC1530.

Contents

Introduction

There are thirteen documents associated with this report that are presented in Appendices A-M. Together they explain: 1) the origin of the MIL-L-87177 lubricant, 2) the USAF's connector corrosion problems on the F-16, 3) tests that Bill Abbott of Battelle Laboratories ran that guided him to select this particular material to protect certain connectors on the F-16's, 4) subsequent Air Force field experience using the lubricant, 5) tests run by Battelle to explore its use in the DOE environment, 6) tests run by New Mexico State University demonstrating its use as a fretting corrosion inhibitor, 7) tests run by Ron Taylor at HFM&T to qualify the lubricant for use on DOE connectors and 8) Sandia studies performed to detect possible materials compatibility issues between the lubricant and other DOE materials and eventually, to qualify it for WR use. Within these references are also documentation of our initial interest in this lubricant, contacts with its maker (International Lubrication and Fuel Consultants), and LLNL's favorable assessment of its use in the DOE environment.

Appendix A: "Shelf Life Concerns on Connectors,"[1] a memo from Ron Taylor to Jim Hanlon introduces the problem of finding connectors in KC stores with corrosion that initiated this work. We (Ron and Jim) had just attended an IEEE Intensive Course On Electrical Contacts where one of the instructors, Bill Abbott from Battelle Laboratories, had told us about the lubricant he was investigating for use by the Air Force.

Appendix B: "Visit to International Lubrication and Fuel Consultants, Inc."[2] documents our first contact with George Kitchen, president of ILFC and developer of the lubricant. In this visit we outlined much of the work that we performed to prove-in the lubricant for use on DOE connectors.

Appendix C: "The Evolution of a Water Displacing Corrosion Preventative Lubricant"[3] was presented by George Kitchen to the NACE (National Association of Corrosion Engineers) conference in April, 2000. Mr. Kitchen describes: 1) the events that lead him to develop his water displacing, non polymerizing lubricant at Bell Laboratories in 1981, 2) the conditions under which it was designed to prevent corrosion, and 3) tests results that demonstrate it does not materially affect insulation resistance of connectors to which it is applied.

Appendix D: "Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors"[4] is a 1996 report by Bill Abbott from Battelle that he generously gave to us some time after the IEEE course. It describes his extensive laboratory and field evaluations of 12 commercially available connector lubricants for the USAF. The MIL-L-87177 lubricant that we have evaluated for use on DOE connectors was one of two identified as affording "a high degree of protection to metallic connector components. At the same time, all data have shown no known engineering (or environmental) risks to operating systems associated with the use of properly qualified lubricants." Mr. Abbott goes on to recommend a "test sequence for connector/lubricant qualification" which we subsequently adapted for our use and performed on the SA1386-3 connector as reported below.[9]

Appendix E: "Corrosion Monitoring of Air Force Field Sites and Effects of Lubrication on Corrosion Inhibition"[5] by W. H. (Bill) Abbott was also presented to the 2000 NACE conference. It summarizes work that he had been doing for the USAF since 1994 showing that the MIL-L-87177 lubricant "can provide almost total corrosion inhibition at electrical interfaces while posing no known engineering risk. At the same time, those same materials will survive comprehensive laboratory testing." It includes results of ground-based studies at fifty Air Force and Air National Guard base field sites and of flight tests over a period of two years on "upwards of 150 aircraft and a variety of LRU's selected from the flight control, avionics, and weapons systems."

Appendix F: The Air Force side of the story is told in another 2000 NACE paper, "Catastrophic Uncommanded Closures of Engine Feedline Fuel Valve from Corroded Electrical Connectors"[6] by David H. Horne, USAF F-16 Fuel Systems Engineer. Mr. Horne describes the fretting and galvanic corrosion problems encountered with the electrical connectors supplying power to the Main Fuel Shutoff Valve that caused him to initiate work with Battelle and finally to deploy MIL-L-87177 lubricant on the F-16's. "Treatment of electrical connectors with the MIL-L-87177A Grade B was so effective in restoring the conductivity of the tin plated pins and preventing continued corrosion that in a test at one Base the aircraft so treated demonstrated a 16% improved mission capable rate. In addition, millions of dollars saved by cost avoidances were documented by treating the aircraft and aircraft ground equipment connectors."

Appendix G: In another NACE paper presented at the same conference, Neil Aukland of The NMSU Advanced Interconnection Laboratory and James Hanlon of Sandia National Laboratories outline how "MIL-L-87177 and a Commercial Lubricant Improve Electrical Connector Fretting Corrosion Behavior."[7] Without the lubricant, these nano-miniature commercial connectors began to suffer fretting after 2,341 fretting cycles and exceeded a 0.5 ohm contact resistance (which was the failure criteria). With additional fretting their contact resistance exceeded 100,000 ohms. MIL-L-87177 lubricant delayed the onset of first failure to at least 430,000 cycles and many lasted over 20 million fretting cycles. Additionally, the contact resistance on these lubricated parts did not exceed 12 ohms until "end of life."

Appendix H: In "Final Report: Evaluation of Lubricants for Corrosion Inhibition on Electrical Connectors,"[8] Bill Abbott reports on work done in 1998 for Sandia in which he identified an appropriate volatile carrier for dilution of the lubricant and determined a minimum, 20% concentration necessary for effective corrosion protection.

Appendix I: In his letter to Ron Taylor dated May 5, 2000, "Effects of Lubrication on the Reliability of Electrical Connectors,"[9] Bill Abbott reports on further work for HFM&T and Sandia in which he developed a lubricant application technique for Bendix-made SA1386-3 connectors and demonstrated that 20% concentration lubricant applied to the SA1386-3 connector remained effective after extensive thermal aging and after exposure of the connector pins to solder temperatures. He identified the MIL-L-87177 lubricant as being reliable for long-term temperatures up to the 100 to 105^{o}C range. He also exposed lubricated and unlubricated SA connector pairs in two field sites, demonstrating in the more severe site that unlubricated SA connectors, both mated and unmated, experienced a significant degree of degradation within 6 months! Under the same conditions, unmated lubricated connectors were completely protected.

Appendix J: In "Connector Lubricant Qualification Report"[10] Ronald Taylor of HFM&T reports on his qualification work of MIL-L-87177 lubricant on PEEK SA2287-7 & SA2288-7 connectors. The lubricant passed our full series of qualification tests as recommended by Bill Abbott, demonstrating that it produced no undesired effects on the connector performance through the extensive series of environmental tests.

Appendix K: Up to this point, we had collected a mature body of data indicating that the lubricant did not adversely affect the electrical functionality of the connectors. What we were missing was an understanding of the long-term aging and material compatibility characteristics of the lubricant (MIL-L-87177) so that we might recommend its qualification for WR use. To that end, we developed a test plan designed to answer the following questions:

- Will the lubricant ever migrate?
- Will the lubricant interfere with the functionality of the electrical connectors?
- Will the lubricant have any material compatibility issues with other systems? (i.e. getter material or optical switches)

In "Final Progress Report (after the last - 150th thermal cycle): Qualification of MIL-L-87177 for Use as a Corrosion Inhibitor and Lubricant on WR Nano-connectors."[11], Ginger De Marquis reports that the results of this materials compatibility study demonstrate that MIL-L-87177 does not interfere with the functionality of certain electrical components (W87 JTA board using nano-connectors) or optical components (optical switch in a UC1530 communication module operating between 850- 900nm). Additionally, the historical data generated by the Airforce, Battelle, Bell Labs and NMSU Advanced Interconnection Laboratory further reinforce that 1) this material has no adverse interactions with a wide variety of plastics and metals, and 2) this material is beneficial towards reducing corrosion in connectors, including fretting corrosion in nano-connectors. De Marquis recommends that this material be qualified for use as a corrosion inhibitor and lubricant on WR nano-connectors.

Appendix L: In "Assessment of compatibility issues associated with the use of electrical connector lubricant MIL-L-87177A,"[12] Bryan Balazs of Lawrence Livermore National Laboratory concludes that "we foresee no detrimental compatibility issues, although it is suggested that a rigorous set of compatibility tests involving this lubricant system with appropriate materials would increase the confidence that there are no negative issues associated with the use of this lubricant."

Appendix M: Finally, we have included the reference for MIL-L-87177A[13], Military Specification, Lubricants, Water Displacing, Synthetic.

Conclusions

Having demonstrated that this material does no harm to connectors and has no migration or material compatibility issues and also that it prevents chemical and fretting corrosion, we have decided to apply MIL-L-87177 Connector Lubricant to all new connectors that go into KC stores. We recommend that it be applied to connectors on newly built cables and equipment as well as material that recycles through manufacturing locations from the field.

References

1. Ron Taylor, "Shelf Life Concerns on Connectors," memo, September 26, 1997.
2. Jim Hanlon and Ron Taylor, "Visit to International Lubrication and Fuel Consultants, Inc." memo, February 17, 1998.
3. George Kitchen, "The Evolution of a Water Displacing Corrosion Preventative Lubricant" NACE (National Association of Corrosion Engineers, April, 2000.
4. W. H. Abbott, "Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors" August 28, 1996.
5. W. H. Abbott, "Corrosion Monitoring of Air Force Field Sites and Effects of Lubrication on Corrosion Inhibition" Paper# 00713, NACE, April 2000.
6. David H. Horne, "Catastrophic Uncommanded Closures of Engine Feedline Fuel Valve from Corroded Electrical Connectors" Paper# 00719, NACE, April 2000.
7. Neil Aukland and James Hanlon, "MIL-L-87177 and a Commercial Lubricant Improve Electrical Connector Fretting Corrosion Behavior." Paper# 00709, NACE, April 2000.
8. W. H. Abbott, "Final Report: Evaluation of Lubricants for Corrosion Inhibition on Electrical Connectors," December 3, 1998.
9. W. H. Abbott, "Effects of Lubrication on the Reliability of Electrical Connectors," May 5, 2000.
10. Ronald Taylor "Connector Lubricant Qualification Report" memo, January 15, 2001.
11. Ginger De Marquis, "Final Progress Report (after the last - 150th thermal cycle): Qualification of MIL-L-87177 for Use as a Corrosion Inhibitor and Lubricant on WR Nano-connectors." October 25, 2001
12. Bryan Balazs, "Assessment of compatibility issues associated with the use of electrical connector lubricant MIL-L-87177A" September 11, 2000.
13. MIL-L-87177A, February 9, 1990.

Appendix A

Ron Taylor, “Shelf Life Concerns on Connectors,”
(1 page)

AlliedSignal
AEROSPACE

Memorandum
Kansas City Division

Date: September 26, 1997

To: Jim Hanlon Sandia Labs

From: Ron Taylor D/464 FM&T

Subject: Shelf Life Concerns on Connectors

From information obtained at the IEEE Intensive Course On Electrical Contacts we learned that over time, corrosion and degradation of the plating can occur even on parts that are plated to specification. Even with minimal environmental aggressive agents, oxidation and the hardener in the gold aggressive can promote corrosion. The storage time in a unmated condition is probably a worse condition than after the parts are in an assembly and mated.

This has prompted me to consider whether some type of shelf life requirement should be imposed on the connectors in stores. This also has prompted me to consider whether a lubricant of some type should be applied to inhibit corrosive effects while in stores.

We have been finding visual plating problems on connector contacts in next assembly inspection. Some are black spots on connector pins others are small spots of Aluminum and other possible corrosion effects. Many of the date codes involved are 83 thru 89. This has prompted the recall of several part numbers for 100% visual inspection.

In the past year we have recalled the following parts: SA1445-13, SA1386-5, SA1445-2, SA1445-25, SA1530-35 and SA1445-7. This has resulted in several thousand parts to inspect. All parts are stored in an unmated condition in plastic bags. No special environmental requirements are in place in the Stores area.. Most of the problems have been on Circular parts that have been in stores for 8 to 13 years.

Can we consider the following issues at our next interconnect meeting? 1) What do we do with aging parts in our inventory? 2) Should shelf life requirements be implemented? 3) Can lubricants provide some measure of protection?

Ron Taylor D/464 Procurement Engineering

Appendix B

Jim Hanlon and Ron Taylor, "Visit to International Lubrication and Fuel Consultants, Inc."
(3 pages)

Sandia National Laboratories
Operated for the U.S. Department of Energy by
Sandia Corporation

Albuquerque, New Mexico 87185-0523

date: February 17, 1998

to: Connector Team et. al.

from: Jim Hanlon and Ron Taylor

subject: Visit to International Lubrication and Fuel Consultants, Inc.

We had a very interesting meeting with ILFC today. Attendees were Rob Sorensen, Terry Ernest and Jim Hanlon from SNL, Ron Taylor from ASFM&T, and George Kitchen (President) and Ray Kashmiri (Vice President and General Manager) from ILFC.

Our purpose was to discuss the use of ILFC's "1006 Contac "lubricant as a corrosion and fretting inhibitor on DOE connectors. This is one of the materials tested by Bill Abbott at Battelle as reported in "Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors." It has been further evaluated by Abbott in a field study on National Guard F-16's. The Air Force has several specifications in place which permit the use of this material as an electrical contact lubricant.

George Kitchen is an old friend of Jim Hanlon's from Bell Labs. George developed the materials used by the Bell System as a contact lubricant, and he is now making and supplying 1006 Contac to telephone companies for that purpose. He supplied us with a copy of the Bell Telephone Laboratories Specification, KS-22659, Water Displacer (Lubricant) and of the Military Specification, MIL C-87177A, Connector Lubricant, Corrosion Inhibiting Compound, Water Displacing, Synthetic, For High Altitude. George wrote the KS specification and made major input to the military specification.

We had not one but two guided tours of ILFC's facility - one of the better uses I've seen for a former bank building in Rio Rancho, NM. ILFC has quite a few pieces of analytical chemistry equipment that are able to detect specific materials at the parts-per-billion level. This equipment is used in other facets of their business, such as analyzing and characterizing fuels and lubricating fluids.

We found out the following information about the 1006 Contac material.

The primary ingredient in 1006 Contac is poly alpha olefin (excuse the spelling, I'm no organic chemist!). The present "thinner" in use is ethyl acetate which has a 25^{o} flash point and is not particularly nice to use. Previously, the thinner had been Freon TF, but it was changed because of its environmental problems. George wants to try out environmentally correct Freon 141B as soon as he can get some. It's made by Allied Signal (!), so Ron is going to help George get in contact with a source of supply. I have the other ingredients written in my notes, but George offered to supply us with the full formula, ingredients and amounts, correctly spelled, so that we can do a compatibility study with materials in our equipment and connectors.

The temperature range for Contac 1006, as presently constituted for use on aircraft, is from -70^o to + 450^o F (-56^o to +232^o C). It could be further customized for our use if necessary, but we Sandia and Allied Signal folks saw no immediate need for any greater temperature range at the meeting.

The thickness of the residual film left after the thinner/carrier evaporates is on the order of angstroms. The film does not flow after the thinner evaporates, rather it "dries in place." There is a die in the material which will fluoresce under black light, so positive inspection proof of lubricant on a surface is easily obtained. General Dynamics, the F16 manufacturer, ran an evaluation and found it to produce no change in connector contact resistance.

Soldering a surface lubricated with Contac 1006 should vaporize or burn it off if the temperature exceeds 450^o. George recommends cleaning a lubricated surface prior to soldering. Freon TF or ethyl acetate will work as cleaning solvents - and probably Freon 141B as well. TCE/TCA and an aggressive cleaning will probably work as well. We may ask Ed Lopez to have a look at the cleaning question.

George said that poly alpha olefin has been used as a contact lubricant for 40 years now, and that the original films are still functional. This allows him to state that Contac 1006 has a 40 year life.

Application can be done in several ways. The Air Force is using dilute material in a mist/spray can (hand pump type) with a nozzle and an 4" extender tube. They use the mist setting for lubricating connector pins and the spray setting for lubricating light bulb sockets. It is possible to get the material in aerosol cans with CO_2 propellant, but that is very expensive in the small quantities we would require. We could also use a dip-and-evaporate technique, but we would have to be careful to maintain the appropriate concentration of thinner in our reservoir. Material could be sprayed into sockets.

The question was raised about whether surfaces coated with Contac 1006 attracted dust. George thinks that the film is so thin that its attraction for dust is virtually nil. We also checked the Battelle Report which says, "This study also examined the effects of dust attraction/collection by lubricants which is often cited as one concern associated with their use. The results indicated that these effects are largely "cosmetic" in nature, as no adverse effects of dust on connector electrical performance were found. To the extent that any effects were observed, all field results showed a net beneficial effect of selected lubricants compared to the unlubricated condition. This means that the positive effects on corrosion inhibition far outweighed any negative effects of dust."

George helped us come up with the following list of things to do in order to use Contac 1006 on DOE connectors.

We have to settle on the solvent to be used. Freon 141B would be best if it works out. Freon TF works well, but we would have to install closed cycle equipment to use it or get a government permit to use a limited amount of it. Ethyl Acetate also works well but has an undesirable flash point.

We need to explore methods of application for our connectors. And we need to verify that we have good electrical connection after coating.

George recommends that we use the “old” MIL-C-87177A Specification because it is a chemical spec rather than a “performance spec.” It would have to be “touched up” to reflect the final solvent system. George offered to help us prepare our spec so that it would contain both the correct chemical formulation and tests that assure material survival. (There is also an “Outline of test sequence for connector/lubricant qualification” on page 80 of the Battelle report which I would like to share with George if we can get permission from Bill Abbott.)

We need to check material compatibility between the constituents of Contac 1006 and the materials in our connectors, our potting and soldering processes, etc. George offered to supply us with a copy of the materials list and a sample of all of the raw materials. Bob Furlong of ILFC will supply us with label information, product designations and manufacturers.

Copy to:

J. O. Harris	1251	D.R. Lemon	D/462 AS FM&T
L. A. Andrews	1251	R.L. Schaldecker	D/462 AS FM&T
T. L. Ernest	1251	J.M. Emmons	D/462 AS FM&T
R. D. Lewis	1251	R.K. Furia	D/462 AS FM&T
R. D. Kilgo	1251	J.W. Hilton	D/462 AS FM&T
J. W. Braithwaite	1832	J.L. Hoisington	D/400 AS FM&T
R. Sorensen	1832		

Appendix C

George Kitchen, “The Evolution of a Water Displacing Corrosion Preventative Lubricant”
(8 pages)

THE EVOLUTION OF A WATER DISPLACING CORRISION PREVENTIVE LUBRICANT

George H. Kitchen
International Lubrication and Fuel Consultants, Inc.
PO Box 15212
Rio Rancho, NM 87124

ABSTRACT

Born in the wake of a major hurricane which wiped out the Homestead Air Force telecommunication system. The product has emerged as a water displacing, corrosion preventive, lubricant which is relatively electrical resistance free.

INTRODUCTION

A hurricane of significant force devastated the Homestead Air Force Base in Florida in 1980 causing the telecommunications system to go down because of water contamination of the switch contacts. Bell System employees acquired all the (A) CRC-226, (B) WD-40 and (C) LPS in the area and sprayed all the office contacts. The office responded immediately and performed well giving the company's people a program for treating all offices similarly attacked.

About six months later the Homestead office experienced many problems and then went down as it had during the storm. Testing found that the materials which had put it back into service had caused it to fail again. The residual products of (A), (B), and (C) had polymerized causing all treated switch contacts to be electrically open and the office to fail.

The author was asked to develop a product that would do everything these other materials would do, but would not polymerize rapidly thus preventing the office follow-up failures. The Lube and Fuels Study Group at Murray Hill Labs responded to this request immediately.

A Table of Requirements was established to judge the new material dubbed KS-22659 (dated September 24, 1981) Water Displacer (Lubricant). It must prevent corrosion under the following conditions (see Table I).

They also performed extensive testing of the new material and it met all of our requirements. Selig Corp. of Atlanta became the AT&T supplier.

The National Sales Representative for the above corporation took this product to General Motors, the Air Force and others to sell. International Lubrication and Fuel Consultants, Inc. was formed by the author at the breakup of the above mentioned supplier. ILFC, now the manufacturer, (see Table II) was asked to modify the formula for high and low temperature applications. The Air Force created MIL-L-87177 from the KS specification, and after testing by Raychem Corp. (see Report Excerpts) the product was used on F-16 Fuel Modules. Mr. Fred Meyer of the Wright-Patterson Research Center in May of 1981 suggested it as a potential replacement for many DOD material applications. Currently it is used on electrical components of high performance aircraft such as the F-16, for telephone central office switching equipment and quick connect distribution bores. It is recommended for cathodic protection rectifier leads, also light bulb bases and sockets exposed to salt air environments. It is very useful on outdoor electrical components for both industrial and residential applications. Others using this product are off-shore drillers, boaters, fishermen, and ocean shippers.

REPORT EXCERPTS

1.0 PURPOSE AND SCOPE

This testing was performed to evaluate the effects of MIL-L-87177 water displacing, corrosion preventive lubricant on the electrical insulation properties and mechanical integrity of the interfacial seals of MTC100 connector inserts.

2.0 SAMPLE DESCRIPTION

2.1 Test Specimen.

The test specimens were two 2-inch MTC100 round wire pin inserts, P/N MTC100-JA2-P11, terminated to short lengths of wire to provide connections for insulation resistance testing. The parts tested were similar to GD part number 16VE049011-2.

2.2 Test Fluid.

The manufacturer of the test fluid is located in Rio Rancho, New Mexico. The test fluid conformed to MIL-L-87177, "Lubricant, Corrosion Preventive Compound, Water Displacing, Synthetic."

3.0 TEST PROCEDURES AND RESULTS

3.1 Test Setup.

The inserts were terminated to short lengths of wire to allow electrical testing. The odd-numbered contacts and the even-numbered contacts of each insert were bussed together into two circuits: odds and evens. This permits measurement of the insulation resistance of multiple parallel paths with one meter reading, and results in a measured value less than the actual value would be for any given pair of contacts. The inserts were tested unmated and were not installed in connectors.

3.2 Procedures and Results.

Insulation resistance was measured initially; then the test fluid exposure sequence was performed. The test fluid was sprayed onto the connector inserts from the aerosol container in which the fluid was supplied. The spray was aimed at the interfacial seal, but overspray covered most of each specimen. After each exposure to the test fluid, the two specimens were allowed to remain in ambient conditions for the times indicated in Table III, and the insulation resistance was then measured. Insulation resistance was measured between the bussed odd-numbered and even-numbered contacts for each insert.

After the final insulation resistance measurement with the contacts bussed, four additional insulation resistance measurements were taken between individual pairs of contacts on each insert. Results were as shown in Table IV. These values represent the actual typical insulation resistance between individual contacts, whereas the values in the previous table are measurements between multiple contacts in parallel.

3.3 Visual Inspection.

After completion of the test sequence the specimens were visually inspected. There was a heavy coating of test fluid on the interfacial seals and contacts, but there was no visible deterioration of the interfacial seals, contacts, or insert bodies.

4.0 DISCUSSION OF RESULTS

As seen in Table 1, the test fluid caused a reduction of the insulation resistance between the two sets of bussed contacts, from an initial value of approximately 1000 gigaohms, to a final value range of between 3.5 and 8 gigaohms. The minimum insulation resistance value was reached after two or three exposures to the test fluid; further exposure cycles did not result in lower insulation resistance values. In each fluid exposure cycle, the lowest insulation resistance was measured shortly after the exposure, and the insulation resistance then increased before the second measurement. This suggests that the fluid undergoes some change after application, possibly drying, that increases its electrical resistance.

As seen in Table 2, the insulation resistance between individual contacts after exposure to the test fluid was considerably greater than the 5-gigaohm minimum requirement for insulation resistance between individual contacts.

After a total of at least 28.5 hours of exposure to the test fluid, no detrimental mechanical effects could be detected by visual inspection of the interfacial seal material or the insert body material.

TABLE I

CORROSION PREVENTION – UNDER THE FOLLOWING CONDITIONS

	(A) CRC-226	(B) WD-40	(C) LPS	CON-TAC
Salt Water	-	-	-	√
*High temperature (350ºF)	-	-	-	√
Low temperature (-70ºF)	-	-	-	√
Short term (0-6 months)	√	√	√	√
Long term (over 6 months)	-	-	-	√
Water Displacing	√	√	-	√
Low Contact Resistance at:				
High temperature	-	-	-	√
Low temperature	-	-	-	√
Short term	√	√	√	√
Long term	-	-	-	√
Lubrication in:				
High temperature	-	-	-	√
Low temperature	-	-	-	√
Short term	√	√	√	√
Long term	-	-	-	√

*This was never tested over time at this temperature. William Abbott has tested the equivalent materials for prolonged times of 500 hours at 105ºC and reports increasing resistance. Therefore, we believe this should be stated as -70ºF to 220ºF for use over extended time periods.

TABLE II

STOCK #NSN 6850-01-260-8055

FORMULATED BY THE MANUFACTURER TO PROTECT ELECTRICAL CONTACTS FROM CORROSIVE EFFECTS OF MOISTURE

Displaces Water With Excellent Resistance To Washout

Lubricates And Protects Under A Variety Of Temperatures

Fortified With Extra Corrosion Inhibitors For Maximum Protection Against The Effects Of Sea Water And Weather

Exceeds Requirements of MIL-L-87177 For Use On Jet Aircraft

Superior Protection For:

- Off Shore Drilling Equipment
- Equipment During Ocean Transit
- Farm Equipment and Machinery
- Aircraft
- Boats
- Automobiles

TABLE III

TEST SEQUENCE AND RESULTS

PROCEDURE	INSULATION RESISTANCE (Gigaohms)*	
	Specimen 1	Specimen 2
Initial insulation resistance	1000	1000
Test fluid exposure #1	--	--
Insulation resistance after 5 minutes	11	11
Insulation resistance after 1 hour	15	13.5
Test fluid exposure #2	--	--
Insulation resistance after 5 minutes	5.5	5
Insulation resistance after 1 hour	8	7.5
Test fluid exposure #3	--	--
Insulation resistance after 5 minutes	4	4
Insulation resistance after 1.75 hour	6	6
Test fluid exposure #4	--	--
Insulation resistance after 5 minutes	4	4
Insulation resistance after 1.75 hour	5	5
Test fluid exposure #5	--	--
Insulation resistance after 5 minutes	4	3.5
Insulation resistance after 1 hour	5	4.5
Insulation resistance after 17 hours	8	8
Test fluid exposure #6	--	--
Insulation resistance after 5 minutes	5	5
Insulation resistance after 1 hour	5	6.5
Test fluid exposure #7	--	--
Insulation resistance after 1 hour	5	5
Insulation resistance after 5 hours	5.8	6.1

*Because the contacts were bussed for testing, these values represent resistance of multiple parallel paths, any one of which was greater than 5 gigaohms, as determined by the testing summarized in Table IV. The specification requirement of 5 gigaohms applies to the insulation resistance between any two contacts.

TABLE IV

INSULATION RESISTANCE BETWEEN INDIVIDUAL CONTACTS AFTER SEVEN CYCLES OF EXPOSURE TO TEST FLUID

SPECIMEN	CONTACT PAIRS	INSULATION RESISTANCE (Gigaohms)
#1	1 – 2	100
	5 – 6	100
	10 – 11	100
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BRIEF BIOGRAPHY OF GEORGE H. KITCHEN

George Kitchen began his career in the Research Laboratories of Atlantic Refining Company. He was part of the team that developed Atlantic Refining's first multivis oil. He worked on high octane components for gasoline as well as hydroforming of fluid systems using catalysts. He pioneered the standardization of steam pumping in petroleum refineries.

After seven years at Atlantic Refining, George went to Bell Telephone Laboratories (the research division for AT&T). Here he was responsible for lubricant and fuel studies for 27 years, working in the electrochemical department within the Materials Research Center. He was in the failure evaluation group that reconstructed the causes of missile failures. He studied aging of fuels and formulated products to retard this aging. Ian Ross, President of Bell Laboratories, at George's retirement wrote "Kitchen made the perpetual storage of fuel possible." He was the first to put molybdenum disulfide in lubricating oil to reduce friction and wear and he investigated the effects of lubricant compatibility with plastics, metal and other materials.

After retiring from Bell Laboratories in 1982, George and his wife Nancy, founded International Lubrication and Fuel Consultants, Inc. (ILFC, Inc.) which he currently operates full time.

Appendix D

W. H. Abbott, "Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors"
(94 pages)

Contract No. F04606-89-D-0034-RZ05

REPORT

Final Report

Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors

To

Hill Air Force Base

Hill Air Force Base, Utah 84056-5825

August 28, 1996

Battelle
. . . Putting Technology To Work

Final Report

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on

Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors

to

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August 28, 1996

by

W. H. Abbott

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Summary

A study was conducted to evaluate the performance of a variety of lubricant coatings relative to their ability to protect gold-plated, electrical connector interfaces against corrosion in a variety of operating environments. The basis for this program was the contention that a significant portion of the no-fault found/CND's/RTOK's (Cannot Duplicate/Retest OK) found in a variety of weapon systems may be related to connector corrosion.

A total of 12 lubricants were evaluated in connector test hardware that was installed at 10 field sites within the United States. This program was restricted to the study of commercial off-the-shelf (COTS) lubricants. All but one of these lubricants had been qualified under one of two military specifications (MIL-C-81309E and MIL-L-87117A). In addition to the extensive field tests which lasted over a period of 1 year, laboratory tests were conducted to validate field findings.

All of the lubricants investigated in this study were demonstrated to be non-conductive (i.e., have good dielectric properties). While this fact often raises questions about their use on contacts/connectors, data will show that they do not interfere with or change the metallic conduction process. In other words, satisfactory lubricants are "transparent" to the contacts and must remain so throughout their useful life.

Results obtained in this program yielded a consistent finding that some lubricants afford a high degree of protection to metallic connector components. At the same time, all data have shown no known engineering (or environmental) risks to operating systems associated with the use of properly qualified lubricants. It is noted that all of the lubricants studied in this program with one exception were qualified to either of the two above specified Military Specifications. Hence, a major conclusion from this study is that both Specifications are inadequate to evaluate performance. Therefore, the term "properly qualified" refers to a comprehensive performance evaluation that was conducted in the laboratory portion of this study. In addition, it is recommended that changes should be made within existing Specifications to include similar performance requirements. This program has identified at least three lubricants which meet these criteria and whose performance, even under severe environmental conditions, cannot be matched by any other commercially available materials.

The studies have clearly shown that all lubricants are not equivalent with respect to either protection ability or possible risks associated with their use. At least two lubricants qualified under MIL-L-81309E were shown to be generally ineffective for corrosion inhibition at a number of field sites and were further shown to <u>degrade</u> connector performance at two sites.

This study also examined the effects of dust attraction/collection by lubricants which is often cited as one concern associated with their use. The results indicated that these effects are largely "cosmetic" in nature, as no adverse effects of dust on connector electrical performance were found. To the extent that any effects were observed, all field results showed a net beneficial effect of selected lubricants compared to the unlubricated condition. This means that the positive effects on corrosion inhibition far outweighed any negative effects of dust.

At the request of the Air Force, one special lubricant was included in this program which had not been qualified to either military standard. This lubricant was demonstrated to cause a degradation of connector performance at virtually every site as well as on a variety of sensor surfaces.

These latter results have led to two important conclusions. First, lubricants must undergo a very thorough qualification process before use on modern electrical or electronic systems. Second, data obtained in this program indicate that existing military standards are not adequate to properly qualify lubricants for such use according to modern concepts of connector evaluation. Recommendations have, therefore, been made in this report either for changes which are required to existing standards or which may serve as the basis for a new commercial/military standard.

This study was mainly directed toward the performance of gold-plated connectors. However, a high degree of corrosion inhibition was also demonstrated for carbon steel sensors by many of the same lubricants. Therefore, it is likely that the effects demonstrated in this work may be applicable to a wide range of metals including base metals as used in power and grounding applications.

In summary, properly qualified lubricants offer a low cost method for achieving a high degree of corrosion protection on separable connector interfaces. It is expected that future studies will define the extent to which this protection may translate to improved system performance, and whether any practical implementation problems exist.

Introduction

Electrical and electronic connectors including those with gold platings as used by the military may experience degradation by thin film corrosion reactions in actual operational environments. A considerable amount of field and laboratory studies have defined the mechanisms of corrosion and have demonstrated that relevant amounts of corrosion can occur even in environments which may be perceived as benign. Such work has also shown that thin corrosion films which may be well below the limits of visual detection (and therefore, not often perceived as "corrosion") can produce system failures including the intermittent/glitch/no-fault-found and failure-without-warning conditions. These conclusions are highly significant, since they involve symptoms of both hard and intermittent failures that not only affect systems availability, but also are virtually impossible or at a minimum very costly to diagnose and prove.

It is known that some types of thin organic/lubricant films will greatly reduce corrosion rates even in adverse environments. In addition, and for those interface conditions where it is relevant, lubricants may greatly reduce the degradation mechanism known as fretting corrosion.

Although the potential benefits of contact/connector lubricants are well documented, lubrication is **not** commonly practiced other than in a few select industrial applications and probably far fewer military applications. In fact, where it is practiced it is more often for reduced **friction and wear** as opposed to corrosion protection.

There are a number of reasons for this situation. However, most may reduce to a condition of **a lack of comprehensive field and laboratory data relating long term performance to lubricant type and to define the incremental benefits/performance enhancement versus perceived risks.** A related and contributing factor is the lack of well defined specifications/performance criteria for the qualification of connector lubricant systems, particularly for military applications.

It is believed that wider application of connector lubrication technology within the military can provide significant benefits. These include increased availability of electronics, reduction of CND's, and reduced costs of maintenance.

The basis for this program can best be summarized from a briefing chart prepared by the F.A.C.T.S. (Fasteners, Actuators, Connectors, and Subsystems) Project Office at Wright Patterson AFB.

All Air Force weapon system managers are experiencing a high degree of Can Not Duplicate (CND's) Bench-Check Serviceable (BCS) and Retest Okay (RETOK) rates. Though there are numerous reasons as to why electronic components are prone to these deficiencies, a prime candidate for such maintenance actions can be traced to corrosion between the connectors. A significant savings in maintenance man-hours can be directly related to the reduction/elimination of corrosion between electronic connectors.

In view of this recognized problem, a four-phase study was initiated for the primary purpose of determining whether a sound technical basis could be established for the use of corrosion inhibiting lubricants. Such a demonstration would require several things. First, and perhaps foremost, would be the demonstration that if lubricants were applied on electrical or electronic systems, there would be no risk of any type to the system. In other words, the lubricants should not degrade or cause degradation of any type.

Second, there should be a demonstration that a high degree of corrosion inhibition could be achieved compared to the unlubricated condition. This requirement simply means that the potential benefits for the use of a lubricant far outweigh the costs associated with implementation and/or any perceived risks.

Third, there should be a demonstration or at least a reasonable expectation that lubricant technology could be implemented in military operating environments and/or repair facilities, by personnel of varying skill levels, with considerable margin for application conditions, and by processes which pose no known health or environmental risks.

In view of the potential benefits of such a low-cost technology and in view of the absence of good technical data, a program was originated by the F.A.C.T.S. Project Office at WPAFB. This program was conducted by Battelle over the period from late 1994 through early 1996. It was designed to develop actual field data on large sample sizes to demonstrate (or possibly refute) the technology. In addition, extensive supporting laboratory studies were conducted to both confirm the field results and to thoroughly evaluate possible risk factors associated with lubricant use on connectors, particularly in severe flight environments.

Background

Lubrication in the form of thin organic films on electrical and electronic connectors is actually a rather old technology. A review of the technical literature on the subject including relevant conference proceedings might suggest that it is a widely used practice. In reality, it is author's opinion that outside of a very few commercial applications, lubrication is not widely practiced. Where it is used, it appears that the objective has been reduction of friction and wear but not corrosion control.(1)

There are many reasons for this situation. However, most reduce to the lack of comprehensive technical data on which to base decisions and judge risk versus reward. This is one of the reasons why the results of this program may be of great significance to both military and commercial practices.

No formal standards appear to exist within industry other than individual company specifications "permitting" the use of lubricants. Again, this practice is primarily for friction and wear reduction. Lubricant selection is often at the discretion of the vendor, but it has been found that commercial lubrication practice has tended to focus on a very narrow range of lubricant types. These are synthetic materials known as the polyphenyl ethers (PPE) with and without small additions of microcrystalline waxes (MCW). While these materials are effective for their intended purpose, at least one recent publication has shown the following deficiencies and/or limitations which bring into question the use of these materials for corrosion control and particularly for military applications.(2)

1. Many lubricants which are effective for wear reduction do not effectively inhibit corrosion.
2. Many lubricants including those which offer corrosion protection appear to degrade at elevated temperatures.
3. Some lubricants which offer potential for corrosion control pose a risk (high resistance development) when subjected to low temperatures.

In effect, the state-of-the-art with respect to commercial lubrication practices is that few lubricants which are familiar to the connector community will pass what may be regarded as modern qualification procedures.(2)

Lubrication practice is actually recognized within the military, but it appears that the use of lubricants has been very limited. Two relevant lubricant standards can be cited. These are: MIL-C-81309E and MIL-L-87177A. The use of both lubricants qualified to these specifications, while apparently permitted, is to our knowledge not widely practiced. The use of 81309 is specifically recognized under an existing technical order (NAVIAR 16-1-540; TO 1-1-689) titled "Avionic Cleaning and Corrosion Prevention/Control" dated 1 April 1992.

The second specification, 87177A, appears to be recognized and its use required under Air Force TCTO1649. The origin of this TCTO appears to be related to a very unique problem involving a specific electrical connector and potential failure mechanism as found on the main fuel shut-off valve (MFSOV) of the F-16 aircraft. This connector utilized a unique material combination of tin-plated pins mated to gold-plated sockets. This gave rise to a unique degradation mechanism known as "fretting corrosion" which is not directly related to the same corrosion mechanisms which are the subject of the present study. However, there are two relevant findings. One is that the use of this particular lubricant did appear to significantly reduce failure rates. Second, controlled flight tests within the F-16 aircraft conducted by Battelle under Contract F04606-89-D-0034-QP09 demonstrated excellent lubricant performance over at least a 2-year period of operations. At a minimum, the latter studies provided some of the first "hard" field data to support the use of lubricants with no known engineering risk to the systems.

At the present time, a number of lubricants appear to have been qualified under 81309E. Not all of these are still commercially available. Two vendors appear to have qualified products under 87177A. Therefore, at a minimum, approximately 12 materials represent Commercial Off-the-Shelf (COTS) lubricant formulations which are qualified to existing military standards.

The 81309 specification does provide a qualification procedure for the lubricant which begins to address potential applications in connector interfaces. Similar requirements for electrical/electronic applications are not found in 87177A. A review was made of the 81309 specification prior to the initiation of this program, and it was Battelle's opinion that the specification does not provide sufficient or thorough qualification procedures as would be required to justify the use of lubricants in modern electronic applications. In other words, existing specifications do not meet the criteria set forth earlier in this report.

In view of this background/state-of-the-art, this program was developed with several objectives. The first was to conduct a screening qualification of all or most COTS MIL-STD applicable items. The term "applicable" refers mainly to the two referenced standards.

A second objective was to determine whether any or all of these lubricants appear to be acceptable for connector applications as judged from comprehensive, modern qualification procedures.

A third objective (assuming success from the second objective) was to select the "best candidates". These candidates would provide the basis for future, large-scale flight tests.

A fourth objective would be to recommend modifications to existing military standards if the results from this study demonstrated such standards to be deficient. A related objective would be to provide the technical basis for creating or at least encouraging the development of a commercial standard.

Finally, a longer range objective would be to implement the findings from this study for wider applications within the Air Force and DoD in general. Not all of these items were within the scope of the current project. However, they are noted, since they were set forth as broader objectives under F.A.C.T.S. Project No. 93-292.

Program Outline

Two parallel studies were conducted as part of this program. Both had the objective of evaluating a maximum of 12 lubricants as applied to a "standard" gold-plated connector test vehicle. The lubricants as will be described were, with one exception, from the 81309 and 87177A categories. One additional material was included for reasons to be discussed at the request of the F.A.C.T.S. Project Office.

One part of the program involved a 1-year field exposure study. The objective of this work was to obtain a statistically significant (in terms of sample size/pin count) body of performance data on all of the lubricants and at a number of field sites which would represent a wide range of environmental types and extremes.

The field study was ground-based (no flight environments) and largely involved sheltered outdoor exposures at Air Force installations. It should, therefore, be carefully noted that this program was biased towards relatively severe environmental conditions and specifically conditions which are far more severe than are believed to exist within military electronics. This approach was taken both for ease of implementation and to obtain results as quickly as possible. It was argued that if positive results could be demonstrated even under severe environmental conditions, the potential benefits could be far greater at the component level. As will be shown, rapid degradation was confirmed in many ground-based environments. However, the results should be viewed for the intended purpose and do not necessarily represent the rate at which degradation will occur at the component level/contact interface.

The original program plan called for the evaluation of a maximum of 12 lubricants and at a maximum of 7 field sites. Data were successfully obtained on 12 lubricants, but for reasons to be discussed, a total of 10 sites were included in the program.

The parallel laboratory study involved exactly the same test vehicles and lubricants. This study was designed to evaluate in a systematic manner effects of the individual environmental variables which are recognized as being of importance to the evaluation of lubricant performance at contact interfaces. This work emphasized the effects of high and low temperatures both for their singular effects and as pre-conditioning tests prior to environmental corrosion tests.

Electrical performance data, as measured by contact resistance, were recorded for all levels of evaluation. These data will be presented in a summary format, but detailed data have been preserved electronically and are available for review by authorized personnel.

Lubricants

A total of 12 lubricants were evaluated. All were obtained from commercial sources, and a detailed list of the lubricants, manufacturers, applicable specifications, and the form in which the lubricant was supplied to Battelle is given in Table 1. Each lubricant has a numerical I.D. (Identifier) attached to it in the left-hand column. This I.D. will be referenced in future data. The I.D. has no significance other than it indicates the order in which the materials were actually procured.

Table 1. Identification of lubricants

ID	Product Name	Manufacturer	Applicable Specification	Form Supplied
1	D5026NS	Zip Chem Products	81309 Type II, Class 2	Aerosol
2	So-Sure	LHB Industries	81309 Type III, Class 134A	Aerosol
3	Spray 706	Sprayon Products	81309 Type II, Class 2	Aerosol
4	ACF 50	Lear Chemical Research	81309 Type II, III	Aerosol
5	CRC 3-36	CRC Industries	81309 Type III	Aerosol
6	Super Corr	Lektro Tech	87177A Type 1, Grade B	Aerosol
7	Stabilant 22	D.W. Elecrochemicals	NA	Liquid (a)
8	NOX Rust 212	Daubert Chemical	81309, Grade II	Liquid
9	Omega 2775	Fine Organics	81309D, Type I, Class 1	Liquid
10	Rust Preventative	Battenfeld-American	81309 Type II, Class 1	Liquid
11	Octoil 5068	Octagon Process	81309 Type II, Class 1	Liquid
12	Alox 2028C	Alox Corp	81309 Type II, Class 1	Liquid (b)

(a) Concentrate; diluted 4:1 with ethyl alcohol.
(b) Concentrate, diluted 2:1 with mineral spirits.

At the beginning of the program, each of the 81309 vendors listed in that specification was contacted. It was determined that not all of the listed vendors are producing a material conforming to this specification. For this reason, several vendors were eliminated from further consideration. In some cases, the materials were readily available as aerosol spray cans. This was desired, since the intent in this work was to apply the lubricant by spraying. This method of application would obviously be the method of choice for field applications.

Other 81309 lubricants were available only in liquid form. Most of these, with the exception of Lubricant 12, were "ready to use" as claimed by the vendor. Lubricant 12 was supplied by the vendor as a concentrate and according to his suggestion, was diluted 2:1 by volume with mineral spirits. The lubricants which are listed as liquid in Table 1 were actually applied by spraying. This was done using a small portable sprayer of the form readily available in artist supply stores. In this case, the propellant was CO_2 available from a small compressed gas source. At this point, it should be noted that all materials used in this program including the propellants and Lubricants listed in Table 1 did meet all requirements of being both nonhazardous and free of any known ozone depleting compounds (ODC's).

Lubricant 6 is the single 87177A Lubricant evaluated in this program. It is believed that at least two vendors exist for this similar material. Even though the material from one vendor was evaluated in this program, no inference should be drawn concerning the relative performance of materials from these vendors. In fact, results from the MFSOV study referenced earlier would suggest that their performance is equivalent.

Lubricant 7 is the only material listed in Table 1 which did not conform to any U.S. military specification. According to the vendor, however, this material is listed under a NATO supply code 38948 and NATO Part No. 5999-21-900-6937. This material was included in the program at the request of the F.A.C.T.S. Project Office on the basis of claims made by the manufacturer for the ability of this material to function as a "contact enhancer". In fact, it is understood that this material has been promoted by the vendor within at least several military services.

Lubricant 7 used in this program was furnished to Battelle by the F.A.C.T.S. Project Office in the form of a standard 15 ml concentrate sample provided by the vendor. This material was subsequently diluted 4:1 by volume with ethyl alcohol. This procedure is consistent with directions provided in the vendor's trade literature and was further confirmed in telephone discussions with the vendor. Lubricant 7 in the diluted form was also applied by spraying.

As a matter of information, it is also worth noting that each vendor was questioned in some detail concerning any studies or other technical information which might be available relative to the intended application. The conclusion from this search was that no data in any form could be provided by the vendors other than to indicate that the material had met the requirements of the existing specifications. It is probably a fair statement that little, if any, technical information was available at the start of this program on the performance of these lubricants in connector applications, even though some vendors were aware or believed that their materials had been used successfully for this purpose.

Test Items

Three test items were used throughout this program in both the field and laboratory. These will be described individually, and each served very different and specific purposes. These are: (1) the test connector, (2) corrosion monitoring/verification coupons, and (3) lubricated steel corrosion sensors.

The test connectors, of course, played the major role in this program and provided a quantitative electrical response concerning corrosion and corrosion inhibition. The corrosion monitoring coupons provided both quantitative and qualitative descriptors of severity levels at the various test sites.

Connectors

Test Connector

The test connector was a commercial, 50-position, vertical, board mount, double-sided, edge-card connector (AMP P/N 530843-5). This component had phosphor-bronze springs which were selectively plated to a specification of 50 microinches of nickel followed by 30 microinches of hard gold. Details regarding the specific plating processes were not known. However, the plating thicknesses were verified by metallographic cross-section as being very close to specified values.

An edge card connector was used in this work for several reasons. First, it has a relatively open structure with minimum shielding effects. In this respect, it should give a realistic, worst case test of corrosion susceptibility. The second reason was experimental convenience in which experimental variables could be controlled by operations on the simulated pc "board" as will be described.

It is immediately recognized that this test vehicle is a considerable departure from the traditional circular military connectors relevant on many LRU's (Line Replaceable Units). While these differences may represent a valid criticism of this work as being too severe a test, its use was justified for the reasons given earlier.

The final variable of importance is contact normal force. The connector springs had a spring rate of 15 to 17 grams per mil of deflection. The simulated pc board had a minimum thickness of 0.055-inch. Therefore, this resulted in a normal force range of about 260 to 300 grams per contact.

The test connectors were soldered into double-sided pc boards specially designed for this study. These pc boards, which could accommodate two connectors each, had solder-plated, edge-card tabs as instrumentation pinouts which permitted a four wire contact resistance measurement to be made via wiring harness attachment to a data scanning system. The edge-card connectors were mounted at right angles to this pc board. An example of this connector test vehicle is shown in Figure 1.

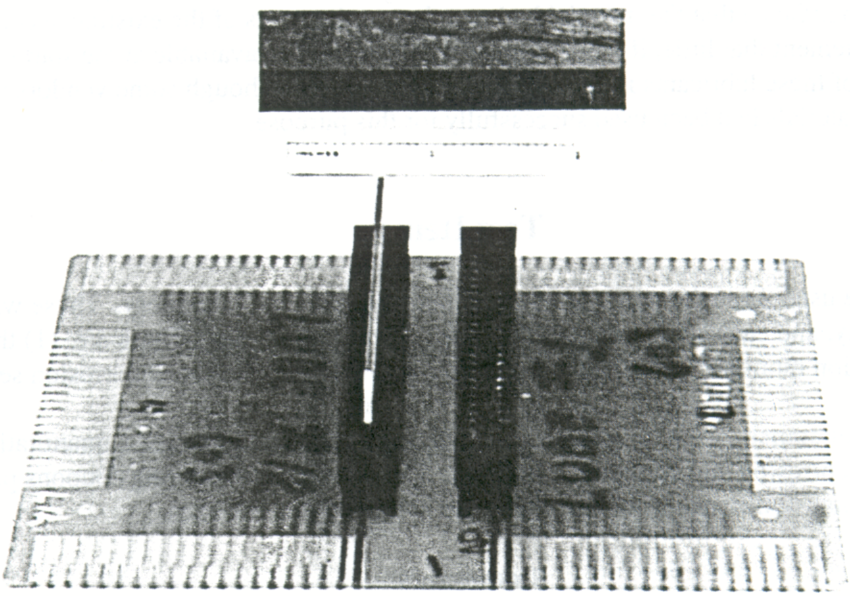

Figure 1. Typical pc card with two mounted test connectors

Simulated pc Boards

The simulated pc boards which were critical in this study, had final dimensions of 0.055-inch thick x 3 inches length x 1.2-inch width. Test samples having these dimensions were sheared from larger plated panels, partly for manufacturing convenience and to simulate a bare copper edge on the entrance end of the board.

The substrates were OFHC (Oxygen Free High Conductivity) copper that were finished by metallographic abrasion to give a standard roughness of 6.9 ± 0.5 microinches CLA (CenterLine Average). For most of the work described in this paper, the finish of primary interest was specified as 30 microinches of an acid-hard gold over 50 microinches of nickel. All of these samples were plated by one commercial vendor as a single large lot.

Plating Thickness

Plating thickness determinations were made on metallographic cross-sections from multiple samples of each type of material. Measurements were made both by optical microscopy at 1,000X magnification and by X-ray imaging using the scanning electron microscope. The results were in good agreement.

The gold-plated samples had very uniform platings. Thickness values were 36 to 42 microinches of gold and 60 to 65 microinches of nickel.

Porosity

The study objective of achieving high porosity platings was met. A standard operating practice at Battelle for porosity determination is to expose samples directly for 1 to 2 days in a Class II, Flowing Mixed Gas (FMG) environment as described later. Such an exposure effectively "decorates" pore sites with corrosion products which can easily be counted. Pore counts at 10X magnification gave relatively reproducible values of 240 to 260 pores per square centimeter.

This level of porosity would normally be considered high for most military and commercial platings. However, in the author's experience, it is actually not unrealistically high. Defects such as submicroscopic pores through precious metal platings to the underlying base metals provide the paths by which corrosion products may emerge onto the precious metal surfaces. In addition, it is well known that porosity levels may be increased in use by various operational practices and stresses such as insertion and withdrawal or even vibration. Therefore, the use of such platings was considered to present another worst case test of the ability of lubricants to protect an interface.

Test Connector Mounting

Figure 1 shows that two physical connectors could be accommodated on each P/C board. These independent samples were allocated to the study of individual variables which in this case was the lubricant. Six boards of this type were, therefore, needed to evaluate the 12 lubricants at each site. In every case and as an important control, a seventh test board was added which had totally unlubricated samples in both test connectors. This information indicates the minimum sample size per variable as measured by pin count was 50 per site and 500 for all sites.

For purposes of field placement, these samples were held in a plastic test rack which resembled a card cage as shown in Figure 2. This rack served several important purposes in addition to serving as a convenient transport device. It will be noted in Figure 2 that the top and bottom of the rack is a solid cover. This provides some nominal protection against direct and artificial impingement of the environment, birds, etc onto the samples. The second feature is that the test rack is a relatively open structure otherwise providing free circulation of the environment including pollutants and dust.

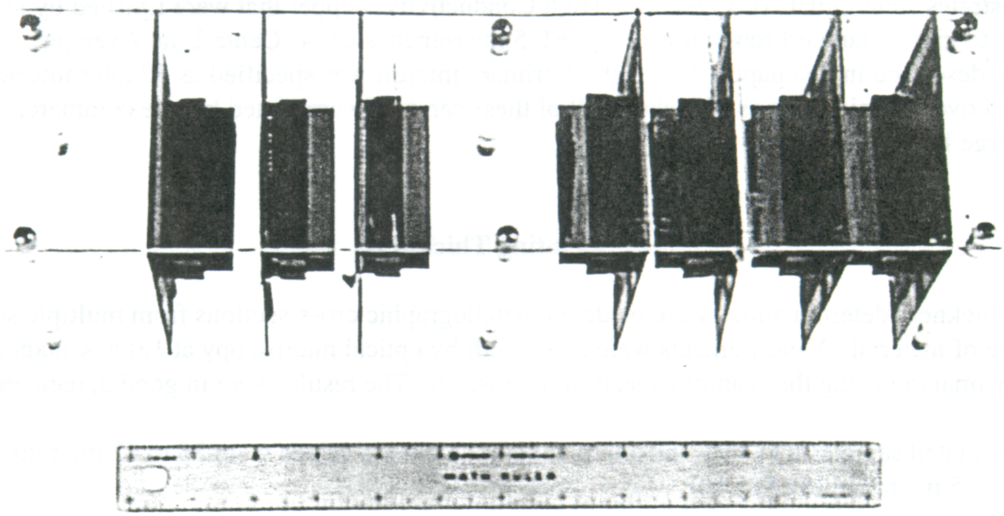

Figure 2. Typical field test fixture

One rack of the type shown in Figure 2 was allocated to each field site. For most laboratory work, it was not necessary to have samples mounted in this manner. Instead, individual cards of the type shown in Figure 1 could be used.

Test Site Documentation

It was considered important to characterize each of the test sites for each of the exposure periods both qualitatively and quantitatively. In theory, it might be possible to make extensive measurements at test sites of a variety of environmental variables. While this would have been both impractical and prohibitively expensive for this program, it has also been Battelle's experience that such data can not be related to corrosion. Instead, the sites were characterized by direct measurements of corrosion in two important ways.

Corrosion Coupons

The first utilized standard Battelle reactivity monitoring coupons. These were designed to provide a quantitative measure of the net corrosive effects of the environment which occurred on a standard matrix of six metal surfaces. These materials were silver, copper, 6061 aluminum, 7075 aluminum, and 1010 steel. References can be found in the technical literature and at least one formal specification[3] for the use of such techniques. Earlier work was done at Battelle in the use of silver and copper for monitoring the indoor environment. This work has been expanded to the use of this broader range of materials for monitoring more aggressive and outdoor environments.

The reactivity monitoring coupons were typically 0.020 by 0.5 by 3.0 inches. Each sample was specially finished on both sides, carefully weighed, and rigidly mounted on 4-inch by 5-inch plastic cards on nylon standoffs. A typical test card is shown in Figure 3. Cards of this type were also mounted in plastic card cages similar to those shown in Figure 2. Cards were typically replaced at 3-month intervals.

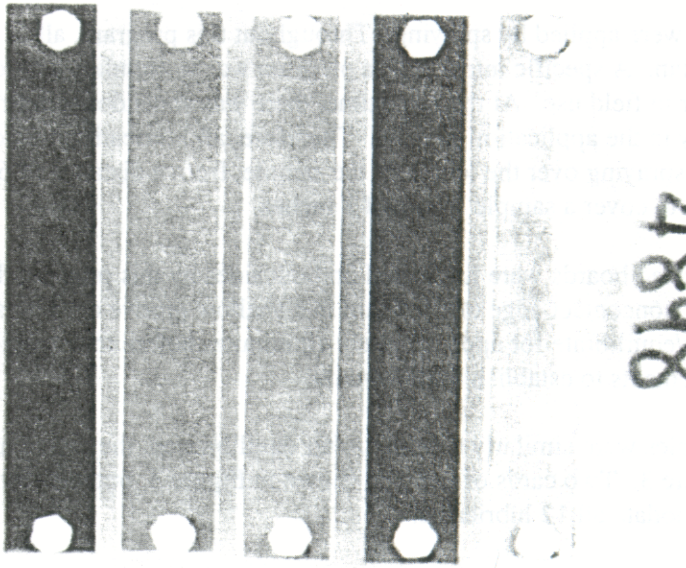

Figure 3. Corrosion monitoring test card

Steel Sensors

The second type of monitoring sample, while quite simple, proved to be relatively effective for the objectives of this program. This was nothing more than a series of steel coupons of the type and dimensions shown in Figure 3, but which were lubricated with each of the 12 materials and similarly mounted on plastic cards. These samples served only as visual sensors of the degree of corrosion which occurred as a function of time. While it is recognized that these data do not necessarily relate to corrosion inhibition on connectors, any significant demonstration of the corrosion inhibition of a material as sensitive as steel could provide a persuasive argument in favor of these lubricants. The lubricated steel cards were also replaced every 3 months.

It is noted that the use of coated/lubricated steel for similar laboratory test purposes is not unique. It is recognized as a test requirement in MIL-C-81309E, Paragraph 4.6, that coated steel samples should survive without visible degradation in a synthetic seawater-sulphurous acid spray test. In addition, MIL-L-87177A, Paragraph 4.6.7.2, specifies a requirement for an elevated temperature, elevated humidity exposure. Unfortunately, there is no known correlation between such exposures and actual field environments. Furthermore, no data are available correlating the results of such tests with the performance of precious metal connectors.

Lubricant Application

The two types of samples to which lubricants were applied have now been described. These are the gold-plated, simulated p/c boards and the steel coupons (except for steel on the weight change card). All lubricants were applied by spraying as described earlier.

In the case of the test connector sample as shown in Figure 1, the lubricant was applied only to the gold-plated cards and on both sides. In the case of the steel sensors, the lubricant was applied to only one side of the coupon.

All lubricants were applied by spraying. Throughout this program, all of the lubrication was done by a single technician. A specific intent in this program was to simulate application conditions and variations as might occur in field use. At the same time, there was some desire for nominal control and reproducibility in the application process. Therefore, all lubrication was done as a hand operation using a single pass of spraying over the length of the sample, from a distance of 6 to 8 inches, and over a period of 3 to 4 seconds to cover a sample length of 3 inches.

As the gold-plated boards were lubricated on both sides by this process, they were inverted and vertically held along the noncontact edge of the board in a shallow groove cut into a plastic holder. Samples were allowed to dry/equilibrate for approximately 10 minutes before they were mated to the test connector for initial measurements to establish baseline data.

The steel samples were similarly treated. After equilibration, they were mounted to test cards of the type shown in Figure 3. Two cards of the type shown in Figure 3, but with lubricated steel, were used at each site to accommodate all 12 lubricants.

During the course of this program, lubrication activities occurred on many test samples. It was, therefore, opportune and appropriate to characterize the degree of lubricant coverage which was achieved for future reference. This was done by carefully weighing samples both before and after lubrication. Additionally, data were obtained after samples equilibrated both at room temperature and after exposure for 24 hours to a slightly elevated temperature of 50 C in a forced air oven. During these equilibrations, each sample was held horizontally in individual narrow-mouth glass jars which were open at the top.

The data from these coverage measurements are shown in Table 2. The data serve only to document what was done and the degree of variability which actually occurred. The data in no way have a necessary correlation to performance. In fact, it will be shown that **no** such correlation exists. Neither is there any correlation between the implied film thickness from these data and performance. These conclusions are fortunate in one respect and immediately indicate that performance at least for the better lubricants is relatively independent of application conditions, i.e., there is considerable margin.

The data in Table 2 may be compared to data published in Ref. 2 for more conventional lubricants applied to identical samples by both dipping and spraying. It is clear from these data that the coating thicknesses achieved with all 12 lubricants were considerably greater and in most cases by at least a factor of 10 compared to more traditional, commercial lubricants. The present results were obtained in spite of the fact that the title of 81309 includes the words "ultra-thin film". This is, of course, a relative term having no necessary correlation to performance. At the same time and in comparison to traditional contact lubricants, all of the materials listed in Table 2 should now be considered as moderately **thick** films.

Table 2. Lubricant coverage on gold plated surfaces; lubricant applied by spraying

	Lubricant Coverage (micrograms/cm2)			
	Initial (24 Hrs @Room T)		24 Hrs @ 50 C	
Lube	High	Low	High	Low
1	1230	517	591	424
2	1800	766	1052	607
3	944	723	399	344
4	2631	1260	2001	782
5	1551	459	489	314
6	498	205	441	162
7	392	264	341	231
8	1595	299	911	259
9	503	437	473	229
10	1647	317	972	273
11	1722	1115	1146	884
12	616	266	375	226

Test Sites

A total of nine distinctive sites were used in this study. These are described in general details in Table 3. For the purposes of this program, they could be described as largely sheltered, uncontrolled (and often outdoor) environments. Nearly all were quite aggressive as eventually confirmed by all monitoring data including the connector data.

All of the sites except those labeled Sites 2 and 3 were at Air Force/Air National Guard bases. Sites 2 and 3 were at Battelle-owned facilities at Daytona Beach, Florida and represented the only locations which were in close proximity to a marine environment, although the two were totally different in severity levels.

Sites 5 and 6 are designated as separate sites even though the samples were physically located within the same hanger and separated by about 300 feet. The purpose of having two sites at this location was to independently study mated versus unmated connector performance. Since this location was known to be "non-corrosive", it provided for a realistic study of dust effects.

The sites were confirmed to represent a wide range of reactivity levels. In addition, they had a wide range of known environmental conditions including the perceived levels of dust. This fact is important to recognize. One of the often cited concerns associated with the use of lubricants is their ability to attract and retain dust. While there is general belief that any such effects are largely cosmetic, it is still a risk factor which must be addressed. We may, therefore, emphasize the fact that it was addressed by virtue of the fact that dust and often high levels of dust were encountered among the sites together with the fact that the test vehicle used is perhaps the component most susceptible to such effects if they will occur.

It should be carefully noted that with two exceptions (Sites 3 and 5), this program was biased towards **severe** environments in comparison to the environments in which most modern electronic equipment will operate. This selection was intentional and for the purposes of obtaining results within a reasonable period of time.

The descriptions in Table 3 show that for most exposures, the connector samples were exposed in the aged-mated condition. However, at each of the two indoor sites (3 and 5), an independent sample set was also exposed in the unmated condition. For this exposure, both the edge-card connectors and the boards were exposed. In this case, the boards were removed from the connector, turned upside down, and the noncontact end was inserted into an independent connector which served only as a permanent sample holder. This procedure was reversed at the time of measurement.

Table 3. Characteristics of field sites for sample exposures

Site No.	Geographic Location	Sample Location	Site Characteristics	Dates of Exposure
1	Ohio Air National Guard; Springfield Airport; Springfield, OH	Sheltered outdoors under air conditioning unit; about 12 inches above cement pad on ground level; outside Bldg 128, avionics	Midwest; moderate pollution; moderate dust; no direct impingement on samples, but good air circulation; all connector samples exposed mated	11/1/94 - 12/18/95
2	Battelle Florida Marine Research Facility; Daytona Beach/ Ponce Inlet, FL	Sheltered, beachfront; inside ventilated, painted aluminum "doghouse", about 25 meters above high tide line and 18" above ground level; no direct impingement of environment on samples; free, natural, air circulation around samples	Pure marine environment; airborne, salt mist; extended periods of high humidity; low pollution; low-moderate dust; all connector samples exposed mated	11/3/94 - 12/15/95
3	Same/near Site 2 but indoors about 1/4 mile away at Battelle/laboratory/office facilities along tidal river	Indoors in storage/office area	Pure marine environment but modified/attenuated by building and human activities; periodic air conditioning; moderate periods of high humidity; moderate air exchange with exterior environment; low-moderate dust; independent connector sample sets exposed mated and unmated	11/3/94 - 12/15/95
4	Texas Air National Guard, Ellington Field; Houston, TX	Sheltered, exposure inside open hanger (Radar Calibration Shed); samples located along wall about 10 feet above ground level	Area of moderate industrial air pollution, high humidity, and aircraft operations; free air circulation around samples but no direct impingement of environment; low dust; all connector samples exposed mated	11/7/94 - 12/16/95
5	Hill AFB; Ogden, UT	Indoors; F-16 production line, Bldg 225; Dock 16, center of hanger on top of cabinet about 7 feet above floor	Low pollution area; low dust; natural air circulation around samples; selected as control but also representative of exposures of unmated connectors during aircraft repair. All connector samples exposed mated	11/16/94 - 12/20/95

Site No.	Geographic Location	Sample Location	Site Characteristics	Dates of Exposure
6	Hill AFB; Ogden, UT	Same as Site 5, but at Dock 21 area about 100 feet away from Site 5; similar type of installation and environment; all connector samples exposed unmated		11/16/94 - 12/20/95
7	Shaw Air Force Base; Sumter, SC	Open hangar at end of runway; similar location/installation as used at Site 4	Inland, low pollution, extended periods of high humidity; moderate dust; area of aircraft operations. All connector test samples exposed mated	12/5/94 - 12/21/95
8	Montana Air National Guard; Gt. Falls, Montana International Airport	Sheltered area on roof of ANG building; no direct impingement of environment, but good air circulation due to windy conditions	Very low air pollution except for possible contributions from aircraft operations (commercial and military); high and low temperature extreme; generally low humidity; moderate dust; all connector test samples exposed mated	12/2/94 - 12/20/95
9	Tinker AFB, Oklahoma City, OK	Industrial Waste Treatment Facility (IWTP), samples located inside open shed in the Metals Treatment Process Area on railing about 10 feet above ground level	High local air pollution due to process emissions of sulfides (TRS) and various halogenated products; very high dust area due to windy conditions and construction in area; no direct impingement on samples but good air circulation around samples; all connector samples exposed in mated condition	11/8/94 - 12/20/95
10	Tinker AFB, Oklahoma City, OK	Indoors at same IWTP Facility, but in Ferrous Sulfides Feed Bldg.; location is about 75 feet away from Site 9. Site added to program due to very high dust collection on Site 9 samples which could obscure effects of corrosion	Uncontrolled environment; high pollution from similar sources as Site 9 but with some attenuation due to building structure; also, low to moderate dust area due to building. All connector samples exposed mated	12/29/94

Field Installation Procedures

Two plastic test racks were actually transported to each field site. One rack as shown in Figure 2 held all of the test connectors. A second, smaller, but similar rack held the weight change and lubricated steel coupons.

All of the installations were done during the months of November and December of 1994. Battelle personnel together with a F.A.C.T.S. Office representative were present for all of the initial sample installations. These installations were relatively simple and involved finding a suitable site and placing the samples in position. At the same time, the program objectives and sample removal procedures were discussed with a designated POC (Point Of Contact) at each of the locations.

Sample transport was exclusively done using overnight delivery services. Test racks were always nominally sealed in polyethylene bags and placed in padded shipping containers. This entire procedure proved to be quite successful and resulted in a zero sample mortality throughout the course of the program

The original program plan and the one which was followed called for sample retrievals every three months over a cumulative exposure period of 1 year. At each 3-month interval, all of the samples were returned to Battelle. The connector test samples were subjected to extensive measurements, and then the same samples were returned to the same field site. With few exceptions, the weight change and lubricated steel coupons were permanently removed at 3-month intervals and replaced with new samples. The entire sample recycling process as just described typically took about 1 week.

Electrical Measurements

Contact resistance was used as the primary measure of electrical performance of the connector interfaces. Such measurements are accepted practice worldwide for judging the quality of an electrical interface in both qualitative and quantitative terms. There is a wealth of supporting data on this topic in the technical literature as well as commercial and military standards. The significant of the contact resistance data will be discussed in following sections. However, for the moment, it may be sufficient to summarize the following features of contact resistance.

1. It is common practice to measure contact resistance under dry circuit (low voltage/low current) conditions, irrespective of the application.
2. Even small changes in contact resistance (milliohms) indicate significant degradation.
3. Contact resistance data on large populations will always show a statistical distribution.
4. The high resistance "tails" of the distributions (magnitude and percentage) directly relate to degradation and risk.
5. As contact resistance increases even slightly, the **probability** of failures as measured by CND's increases.

The measurement conditions used in this work were 50 millivolts open circuit voltage, 10 milliamperes dc current. The measurements were done at Battelle's Columbus Laboratories as samples were returned. Initial measurements were, of course, made to establish baseline data. The test boards shown in Figure 1 shows a series of edge-card tabs on the double-sided pc board. These tabs provided the pin-outs for resistance scanning of the samples after the board was plugged into a mating connector, which in turn was interfaced to a data scanning system.

All samples were actually measured twice upon return. One set of readings was taken in the as-received condition. These measurements will be referenced as the "undisturbed" readings. Thereafter, each gold-plated, simulated pc card was slightly moved once and fully reseated after which the sample was again measured. This will be referenced as the "disturbed" data set.

The last actions represented a deliberate intent to be certain that relative interface motion was factored into the measurements. This procedure is becoming a common commercial practice. If it is not included, important information can be missed concerning potential risks and the degree of degradation which actually has occurred.

The basis for disturbance is two-fold. First, corrosion products, dust, debris, etc may be present around the periphery of the true contact area. As an interface moves in practice and even by submicroscopic amounts, the key to the events which happen next are determined by both the degree of degradation and the ability of the interface to mechanically disrupt those insulating products. The second point is that real interfaces in service do move as driven by such factors as differential thermal expansion, vibration, and shock.

Contact resistance is recognized as being of importance in 81309. However, this specification appears to address only the initial effects of a lubricant on an electrical interface and only to the extent that there should be "no significant increase in resistance between connected pins". Furthermore, no specific failure criterion are stated. As a point of reference and based on accepted commercial practices, we will offer the opinion that in order for a lubricant to be considered as acceptable, it should exhibit **no** initial measurable effect on contact resistance, i.e., its presence should be "transparent" to the metallic interface. Finally, it is noted that 87177A makes no reference to contact resistance as a qualification practice. However, exactly the same principles should apply for any lubricant.

Field Coupon Evaluation

Evaluation of 3-month field coupons was done in two ways. The various weight change coupons as shown in Figure 3 were carefully weighed to the nearest 10 micrograms. These data were compared to initial measurements and from these data weight gain values were calculated. The weight gain data present a direct measurement of the chemical severity of the environments. In addition, these data may be compared to other databases developed by Battelle for both indoor and outdoor environments as well as in aircraft environments to put these numbers in proper perspective.

The lubricated steel sensors served only as visual sensors of the degree of corrosion/rust which occurred. While such an evaluation may be somewhat subjective, it proved to be a very effective means of distinguishing the corrosion inhibiting abilities of the various lubricants. Of equal importance, is the finding from this program that there now appears to be a good correlation between such visual effects and corrosion inhibiting ability for gold-plated electrical connectors. Such results may, if further verified, provide a potentially important part of a test method.

Laboratory Evaluation

Extensive laboratory experiments were run over the course of about 1 year. Emphasis in this work was placed on evaluating those environmental variables and/or risk factors considered to be significant for the use of a connector lubricant.

It has been common practice for military standard environmental/corrosion tests to involve only temperature-humidity aging and/or some form of salt spray test, as found in MIL-STD-202F. While such tests may be important in any qualification program for specific purposes, there is a growing body of data obtained over the last decade to indicate that such tests are either unrealistic or inadequate to evaluate long-term aging/corrosion by operational environments. This is particularly true for avionics environments as shown in recent aircraft monitoring programs conducted by Battelle.(9)

A good review of this subject area may be found in Reference 10. However, it may be sufficient at the moment to summarize that most long-term aging reactions represent the combined effects of low levels of critical pollutants in the environment together with even moderate levels of humidity. These synergistic effects have typically not been addressed in existing military specifications.

Initial Contact Resistance

Each of the materials was characterized to determine the contact resistance distributions in the actual product and for the lubricant coverages listed in Table 2. All contact resistance measurements were made under dry circuit conditions (50 mv, 10 ma) and for a minimum sample size/pin count of 500.

The objective of this work was to document whether metallic asperity contact could be established through each of the coatings and that there were no characteristics of the coatings which might interfere with electrical conduction. Any adverse effects would be revealed by a high resistance "tail" in the extreme of the distribution.

Contact resistance measurements were typically made on the first mating cycling after the simulated pc board was treated. In addition, for many of the coatings, measurements were repeated after durability cycling up to a maximum of about 100 insertion/withdrawal cycles. The temperature at which all of these measurements were made was 23 ± 1 C.

Low Temperature Performance

It is known that some product applications exist in which performance must be maintained at extremely low temperatures. Few data are available in this subject area other than one reference to earlier studies by Antler (5) in which connector pins lubricated with both the 5- and 6-ring polyphenylether materials were evaluated at the lowest temperature of -23 C.

In the present studies, measurements were made to temperatures as low as -60 C. Measurements were made at intervals of 20 C between room temperature and -60 C for both heating and cooling cycles.

For this purpose, the card-mounted test hardware described earlier was used. This was assembled with wiring harnesses routed out of a programmable temperature chamber in which the sample assembly was suspended. This provided the means by which contact resistance measurements could be made *in-situ* at each temperature hold point.

The entire test fixture had one additional provision which provided an extremely important function. This was to impart a small but controlled amount of relative motion to the contact interfaces. The technical basis for including the effects of motion--even single motion events--has been previously discussed[6,7]). In fact, it may be argued that if the effects of motion/disturbance are not included in such an evaluation, results may be totally misleading and may often show little effect.

The mechanism by which small amounts of relative motion were forced to occur relied on differential thermal expansion. A device was constructed to which the free end of the simulated pc board could be firmly attached. This grasping device was secured to the pc board by four stainless steel posts mounted at the card corners and having a length of about 2 inches. In effect, it was the expansion and contraction of the stainless steel posts which controlled the amount of linear motion between the edge-card connector and the simulated pc board.

This device was constructed on the basis of known thermal expansion coefficients to provide motion of a few mils over the temperature range studied. However, the test device was also instrumented with a linear displacement transducer to provide an indication of the motion which did occur. This showed that over the temperature range from +25 C to -55 C, the linear movement at the contact interface was approximately 8 mils.

Thermal Aging

Questions regarding the long-term stability of lubricants are an important concern to users. The term "stability" may refer to several degradation mechanisms. One is the loss of lubricant by mechanisms such as migration and/or vaporization [6]. According to these mechanisms alone, a worst case situation would be that no lubricant remained to perform its intended function. While this could represent the situation for single component, fluid lubricants, a more complex situation could arise with multi-phase lubricants at mated contact interfaces. In this situation, one constituent might be lost to leave behind in the periphery of the contact region large amounts of an objectionable second phase.

In addition to these loss mechanisms , another area of concern is long-term degradation of the lubricants by oxidation. In this case, possible property changes and the formation of hard, non-conducting constituents could adversely affect reliability.

In consideration of these important degradation mechanisms, thermal aging experiments were conducted in several ways. These were done both as independent tests and as conditioning exposures prior to subsequent corrosion tests.

Coupon Aging

In these experiments, the gold-plated, simulated pc boards were lubricated in the normal manner. They were then aged at elevated temperatures after which they were inserted for measurement into separate, unaged edge-card connectors.

During thermal aging, the samples were held in a horizontal plane in order to avoid lubricant pooling at any ends or edges. Individual samples were contained inside small glass bottles open at one end. The glass bottles were sized such that the coupons contacted the glass only along two edges. Bottles of this type were placed inside large circulating air ovens which were controlled to ±1 C.

The time-temperature conditions of thermal aging were 125 C for 500 hours and 80 C for 1,000 hours. These conditions were not arbitrary. As part of this and other ongoing studies, data have been obtained on the kinetics of lubricant loss from both gold-plated coupons and lubricant-filled vials. One objective of this work has been to determine whether these kinetic processes follow an Arrhenius relationship. If this could be verified for a variety of lubricants, then there is at least some basis for the extrapolation of elevated temperature aging data to lower temperature service conditions.

Data obtained to date would suggest that the approximate acceleration factors between aging temperatures of 125 and 80 C versus an assumed average service temperature of 40 C are on the order of 1,000 and 100X, respectively[5,8] . If these numbers are even approximately correct, they would indicate that the thermal aging conditions used in this work represent a minimum of 10 years thermal equivalent at 40 C and considerably longer times at lower temperatures.

Connector Aging

Similar thermal aging experiments were conducted on lubricated and aged-mated hardware. In these experiments, the aging conditions were limited to 80 C for 1,000 hours. This temperature was well below the maximum service temperature of 90 C specified by the connector manufacturer. At 80 C, neither significant plastic degradation nor stress relaxation of the springs was expected.

At the completion of the aged-mated exposures, contact resistance measurements were immediately made. Thereafter, interfaces were intentionally disturbed/moved to determine possible effects of any degradation products accumulated around the periphery of the contacts.

Corrosion Exposures

The corrosion exposures used in this work did not conform to any existing Military Standard. Historically, the latter have emphasized only humidity, temperature, and in some cases, salt fog types of exposures.

Over the last decade, there has been a growing body of evidence that such exposures do not simulate corrosion conditions actually found in field environments at the component level. This realization has lead to the development and widespread use of the Mixed Flowing Gas (MFG) environments. These environments combine the critically important interactive effects of low level air pollutants and even moderate levels of humidity to "drive" many of the natural, corrosion reactions found in practice.

The corrosion exposure used to evaluate inhibition by the various treatments was a Class II FMG environment having the following composition:

10 ppb - H_2S
200 ppb - NO_2
10 ppb - Cl_2
70 percent relative humidity
25 C.

This environment is one of several types which have been developed in recent years to simulate long-terms reactions in electronics operating environments.[10]

For the purposes of this program, it was decided to conduct the evaluations by exposing only the simulated pc boards having the treatments listed in Tables 1 and 3 in the Class II FMG environment. While this type of unmated exposure may be considered severe, the work was done in this manner for two reasons. First, unmated exposures, at least for short periods of time, are realistic of field usage. Second, unmated laboratory exposures are a requirement of qualification procedures. Common requirements among individual companies may be for unmated exposures for periods up to about 5 days. However, at least one well-known requirement is for 10 days of unmated exposure[11].

The procedure typically followed in this work was for the treated cards to be exposed in the Class II environment. Typically at 2-day intervals, samples were removed from the test chamber, mated to a dedicated but unexposed edge-card connector, and measured. Typically, the measurements would consist of contact resistance data at the first mating and then after one durability cycle. Exposures were typically continued in this manner until at least 20 percent of the sample population showed contact resistance increases exceeding about 20 milliohms or for a maximum exposure period of 20 days.

One final type of study was done in conjunction with the flowing mixed gas exposure. This work independently addressed the question of whether surface treatments/lubricants may provide any cleaning action to contact surfaces which have been degraded prior to the treatment.

For this study, gold-plated coupons were degraded by exposures of 2 to 4 days in the Class II environment. Samples were then mated for measurement, unmated, lubricated, then remated for further measurements.

During the course of this work, additional exposures were made to test various aspects of lubricant performance. This included, for example, initial durability cycling of lubricated gold samples up to 100 times prior to corrosion testing. This imposed a relatively severe test to evaluate whether the lubricants prevented wear or if they did not, whether the lubricants would still provide significant environmental protection of the underlying reactive base metals (nickel and/or copper).

Finally, lubricated steel sensors were included in a number of the laboratory exposures. The purpose of this work was to examine whether qualitative correlations did exist with field observations on similar samples.

Test Results

Initial Contact Resistance

The statistical distributions of the initial contact resistance for all field samples are shown in Figures 4 and 5. Since this data format will be used throughout this report to describe the electrical response of samples, a detailed explanation is appropriate.

Figures 4 and 5 represent log probability distribution plots of contact resistance for approximately 1,000 contacts for each lubricant type. These are data obtained on the samples prior to placement in the field. This type of data presentation is relatively common for work of this type.

The results show a distribution of contact resistance values for each case. It should be noted that the data are not true contact resistance, but instead represent total resistance in the circuit path between the points of measurement. The total resistance represents the sum of what should be a <u>constant</u> bulk resistance for each circuit path plus the actual interface resistance. It is known that in the absence of corrosion, the true contact resistance should be on the order of 1 milliohm. The distribution in the data between about 1.5 and 7 to 8 milliohms, therefore, reflects mostly a difference in the constant bulk resistance values for each circuit. These differences present no technical problems, since data were stored electronically for each and every contact. This means that a more precise analysis could be done of effects based on contact resistance change distributions (delta R). Due to the nature of the data which were obtained, such a precise analysis was not required.

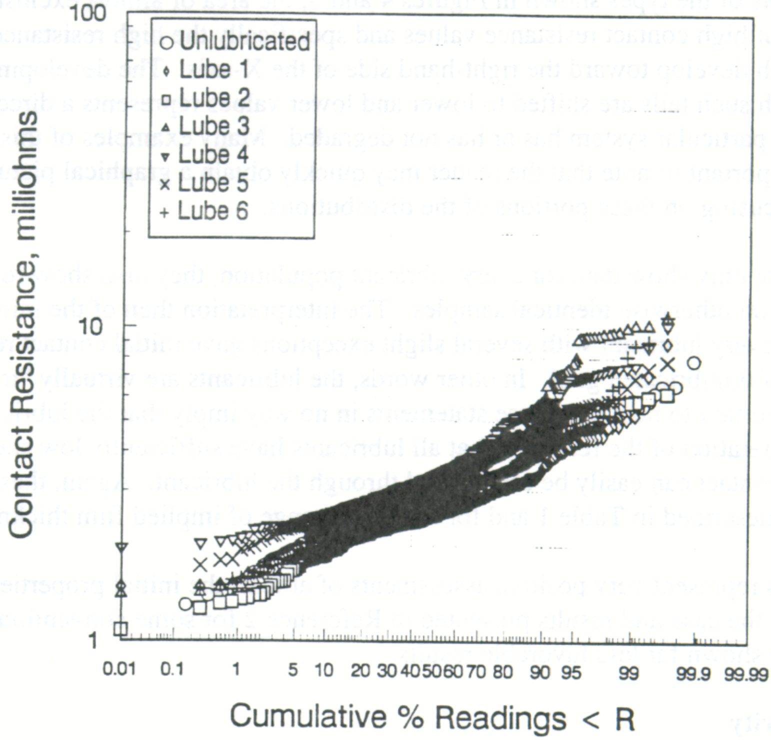

Figure 4. Initial contact resistance of lubricated and unlubricated, gold-plated test boards for field exposures

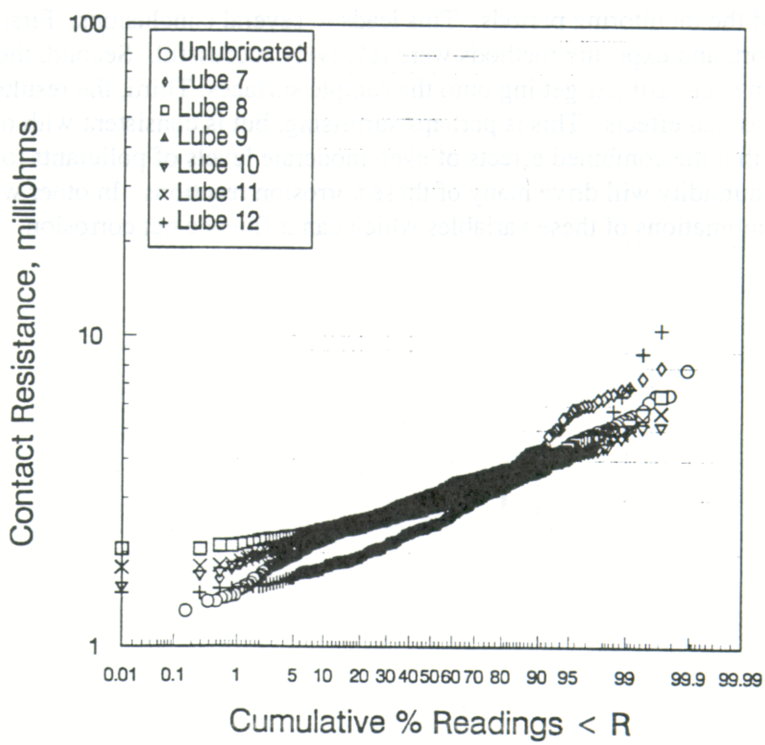

Figure 5. Initial contact resistance of lubricated and unlubricated, gold-plated test boards for field exposures

In distribution plots of the types shown in Figures 4 and 5, the area of almost exclusive interest involves the development of high contact resistance values and specifically the high resistance "tails" of the distributions which develop toward the right-hand side of the X-axis. The development of such tails and the extent to which such tails are shifted to lower and lower values represents a direct measure of the degree to which a particular system has or has not degraded. Many examples of this behavior will be given, and it is important to note that the reader may quickly obtain a graphical picture of the degradation process just by focusing on these portions of the distributions.

Figures 4 and 5 not only show data for every lubricant population, they also show reference data for unlubricated gold on otherwise identical samples. The interpretation then of the initial values is rather straightforward. Every lubricant with several slight exceptions gave initial contact resistance distributions **identical** to that of unlubricated gold. In other words, the lubricants are virtually "transparent" to the contacts. It is important to note that these statements in no way imply that the lubricants are conductive. Instead, the interpretation of the results is that all lubricants have sufficiently low shear strength that metallic asperity contact can easily be established through the lubricant. Again, these results were obtaine for the lubricants described in Table 1 and for the broad range of implied film thicknesses in Table 2.

These conclusions represent very positive assessments of at least the initial properties of these systems. This is not always the case and results presented in Reference 2 for some conventional lubricant formulations have shown far less favorable results.

Field Site Reactivity

A complete summary of the field site reactivity monitoring is given in Figures 6 through 12. Certain conclusions can be reached from these data as discussed in this section.

First, the data are relatively well behaved. This means that there were not recorded any unusual weight changes over any of the monitoring periods. This leads to several conclusions. First, the entire sample preparation, transport, and exposure methods were relatively successful. Second, the objective was achieved without unusual artifacts getting onto the sample surfaces. Third, the results do not appear to show any strong seasonal effects. This is perhaps surprising, but is consistent with other Battelle studies which have shown that the combined effects of even moderate levels of pollutants together with even moderate levels of humidity will drive many of these corrosion reactions. In other words, there does exist wide number of combinations of these variables which can influence net corrosion.

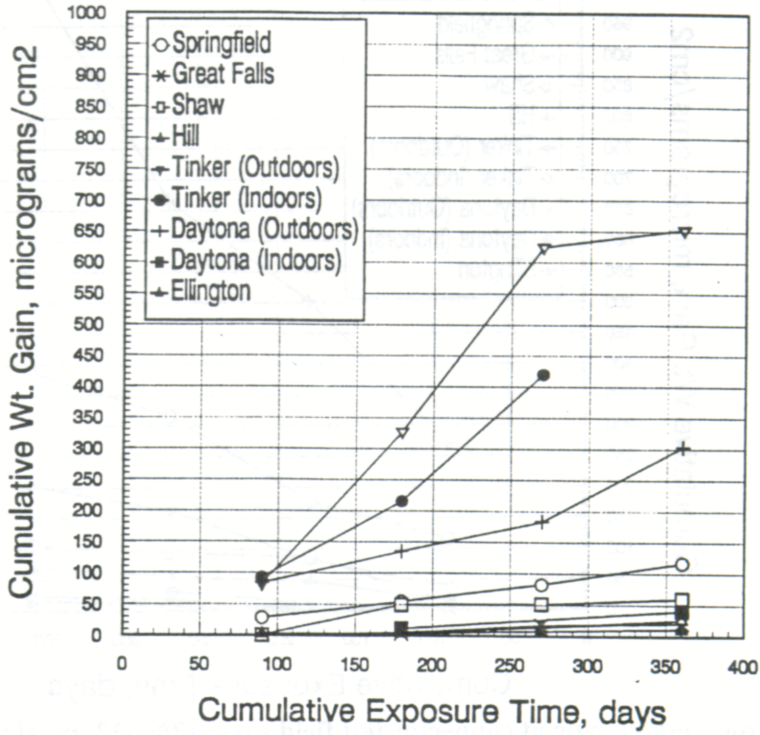

Figure 6. Corrosion monitoring at connector test field sites; 12/94-12/95; silver

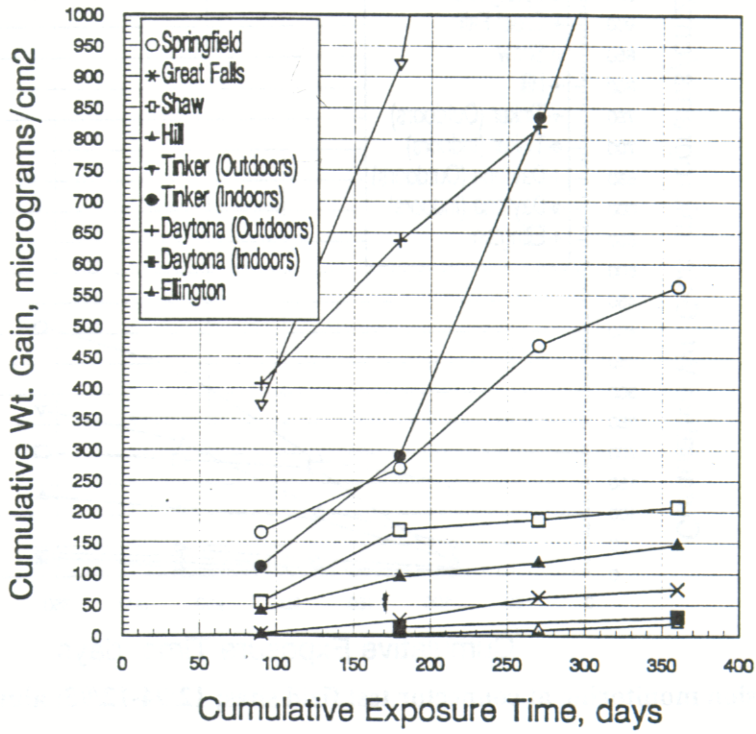

Figure 7. Corrosion monitoring at connector test field sites; 12/94-12/95; copper

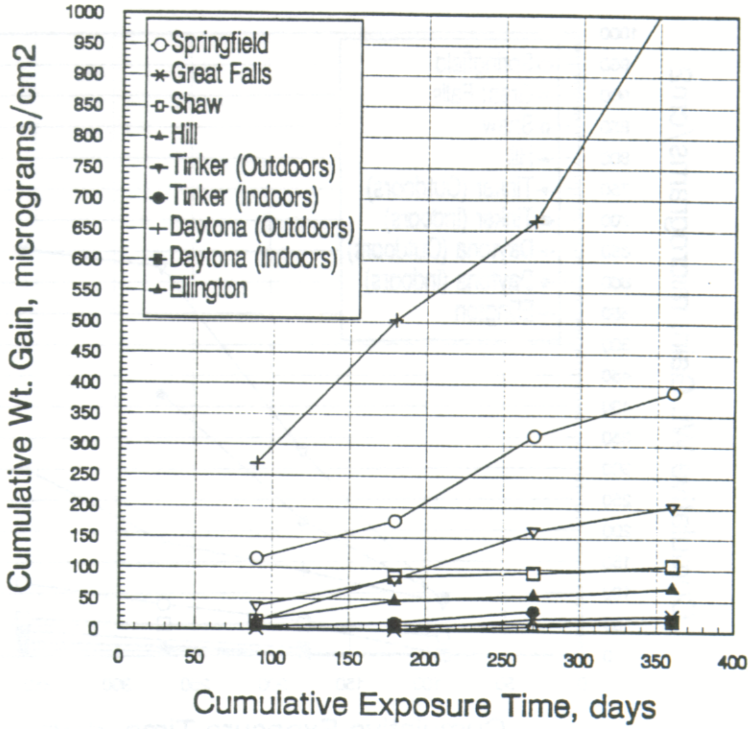

Figure 8. Corrosion monitoring at connector test field sites; 12/94-12/95; aluminum, 6061-T6

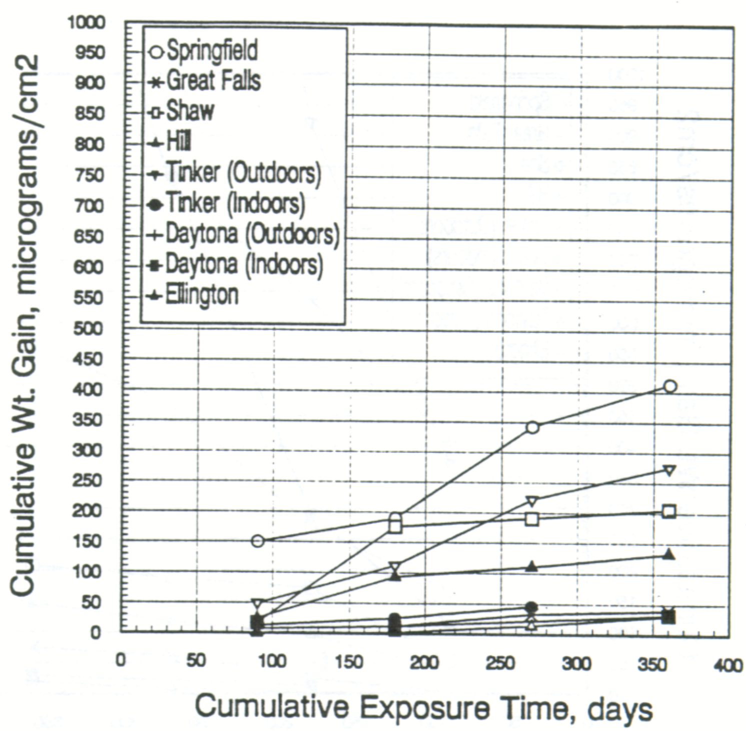

Figure 9. Corrosion monitoring at connector test field sites; 12/94-12/95; aluminum, 7075-T4

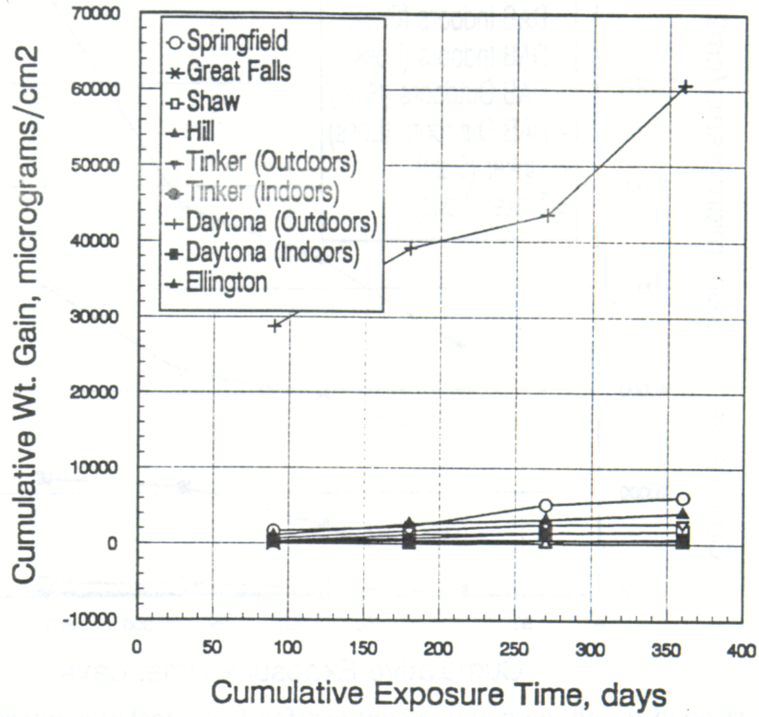

Figure 10. Corrosion monitoring at connector test field sites; 12/94-12/95; steel 1010

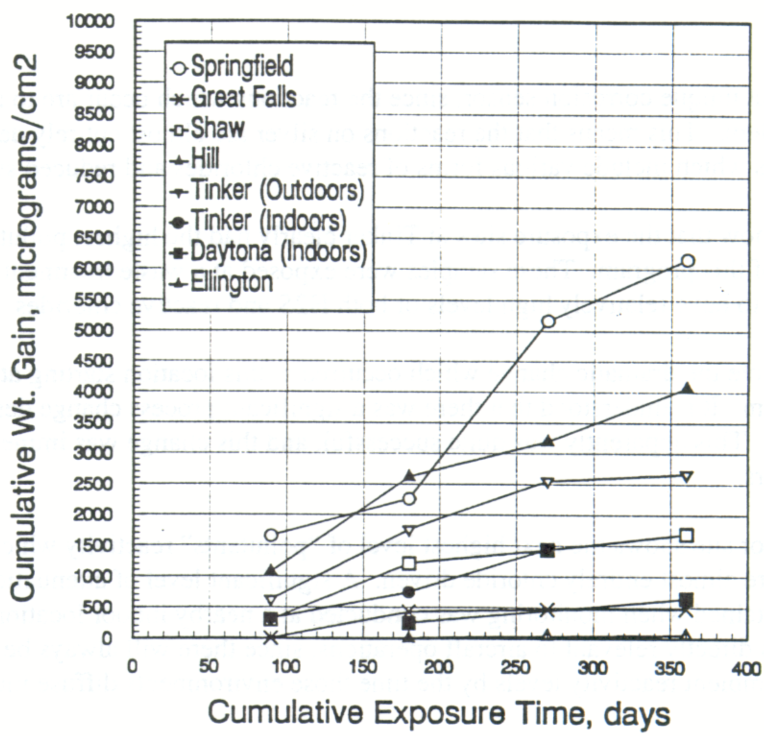

Figure 11. Corrosion monitoring at connector test field sites; 12/94-12/95; steel 1010

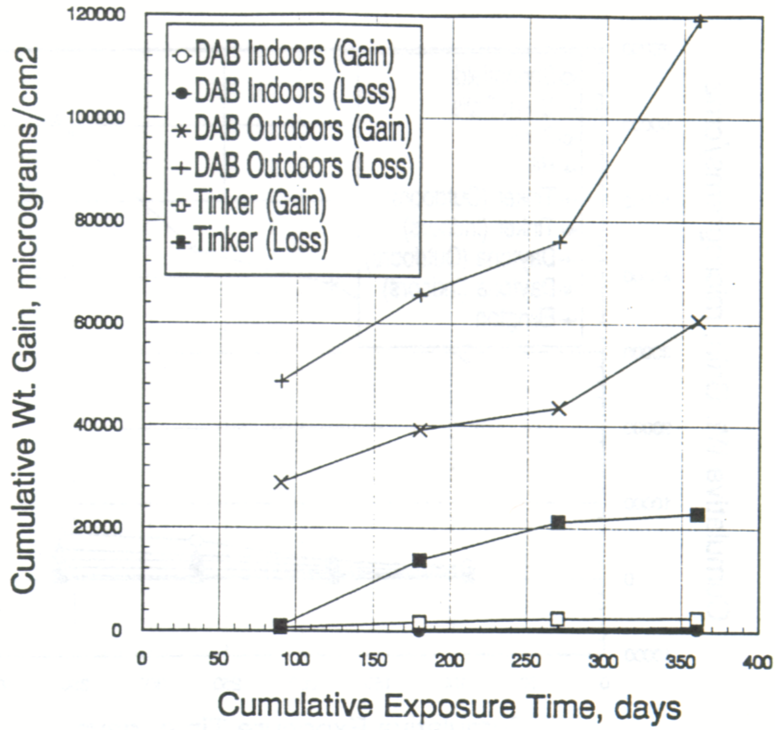

Figure 12. Comparison of weight gain and weight loss for 1010 steel at connector test sites; 12/94-12/95

Silver

Silver is a somewhat unique corrosion sensor, since the reactions which occur are to a large degree humidity **independent.** This means that the reactions on silver are almost entirely dependent on the levels of critical pollutants which include various forms of reactive chlorides and reduced sulfide species (H2S).

The silver results show that the exposure sites at Tinker clearly had the highest pollution levels for at least the first 9 months of this program. These samples were exposed at a waste treatment facility (IWTP) which were known to have relatively high levels of both H2S and reactive chlorides.

It is interesting to note the dramatic change which occurred at this location starting at about the 9-month point of this program. It is understood that there was a significant process change designed to lower the levels of emissions. This apparently was quite successful, and this change was immediately picked up by the corrosion sensors.

The Daytona outdoor site shows the next highest level of "pollutants" reactivity which might be expected. These reactions were almost entirely chloride driven. A significant level of attenuation by more than a factor of 10 was obtained when monitoring was conducted at a nearby indoor location. This same attenuation effect is directly relevant to aircraft operations, since there will always be a significant attenuation of the ambient reactivity levels by the time those environments diffuse into the LRU's or other electrical systems.

Copper

The copper data are particularly significant, since the use of this material for monitoring purposes has been developed into a U.S. national standard (Ref. 3) and is being used worldwide. In fact, Battelle has used the same monitoring method for characterizing the environments inside a number of Air Force aircraft, including most recently the F-16.

The results in Figure 7 should be viewed in the following way. The degree of reaction which has occurred on copper is a direct measure of the chemical severity of the environment as relevant to the problem of electronics corrosion. In this respect, the Tinker, Daytona Beach (outdoor), and even Springfield sites are regarded as very severe. In fact, it could be stated with a high degree of confidence that if any modern electronics were required to survive direct exposure (at the component level) in environments this severe, the probability of survival would be regarded as almost nil. The same conclusions would be reached for the environments at Shaw, Ellington, and Great Falls even though the environments are far less severe. It is only at the reactivity levels shown for the two indoor locations that the reactivity levels are approaching the levels desired to assure the reliable performance of modern electronics including connectors.

It might, at first glance, appear that reliable operation should not be attainable. The fact that it is in many military applications is, we believe, largely due to the fact that the real environments in proximity to the electronics are at levels at or below those shown in Figure 7 for the two indoor locations. There is some basis for this conclusion in monitoring studies already conducted by Battelle for the military. In other words, the real environments inside aircraft, the "Black Boxes", etc are normally at these low levels. It will be shown that even though these low levels <u>do not</u> prevent corrosion entirely. At a minimum, however, they are sufficiently low to significantly reduce the magnitude of the problem.

In summary, the copper data confirm that the objectives of obtaining both severe and very diverse types of environments were obtained.

Aluminum

The results for two types of aluminum are shown in Figures 8 and 9. These data are in general agreement with the previous monitoring data with several notable exceptions. These involved the Tinker sites. It is known that the corrosion of aluminum is highly dependent on the levels of reactive chlorides in the environment. This can include chloride species others than sodium chloride as shown by the strong response of both types of aluminum at the Springfield Airport which is far removed from a coastal location. It is also shown in the data at Tinker that the reaction rate of aluminum was relatively low. This was attributed to the overwhelming pollutant effect of sulfides and relatively low levels of chlorides. It is not surprising that the outdoor Daytona site showed the highest aluminum reactivity level.

The data in Figures 8 and 9 do show differences between the two grades of aluminum even though both were reactive. At nearly all sites, the 7075 aluminum did react at a higher rate than 6061. This effect was particularly noticeable at the outdoor Daytona site. The 7075 data in Figure 9 is not apparent, since the numbers are off-scale. As a matter of record, it is noted that the actual numbers for 7075 would be 1445, 2324, 2426, and 4423 micrograms/square centimeter at 3, 6, 9, and 12 months, respectively.

The results for aluminum are presented even though they are regarded as being of least importance to the problem of electronics corrosion and related monitoring. This fact was clearly noted in the results at Tinker, since the gold-plated samples did show extremely strong response to the sulfide-rich environment.

This observations provides further support to the conclusion that the use of sensor data from materials such as copper are more relevant to the electronics corrosion problem.

Steel

The weight gain results for low carbon steel are shown on two scales in Figures 10 and 11. These results also correlate relatively well with earlier results and conclusions concerning the strong chloride effects on many materials. For reference purposes, it is worthwhile noting that by this method of analysis, the approximate threshold level at which visual corrosion of steel would be found is approximately 20 micrograms/square centimeter. This is consistent with the observation on the samples that the only location in which steel was not visibly corroded within 1 year was the indoor location at Hill Air Force Base. The absence of rusting at this location could be attributed to both the low humidity and low chloride levels. Similar observations were made for very short-term (3-month) exposures at both Great Falls and the Daytona Beach indoor location.

As a matter of technical interest, the data in Figures 10 and 11 actually understate the degree of corrosion which occurred on steel at the more severe locations. The reason for this is well known and lies in the fact that once corrosion proceeds beyond a certain point, films are no longer adherent and may be lost by flaking. For this reason, it is common practice to chemically remove nearly all corrosion products from steel surfaces (ASTM Specification G1-82). The resultant weight change will be a loss rather than a gain. Results of such analysis are shown in Figures 12 and 13 and a direct comparison is made between the two methods. The results clearly show that for the severe locations (Daytona, Springfield, Tinker) weight gain tends to understate corrosion by factors of 2X to 3X. Conversely, for much lower corrosion rates as would be expected indoors or even within aircraft, the two methods yield nearly identical results.

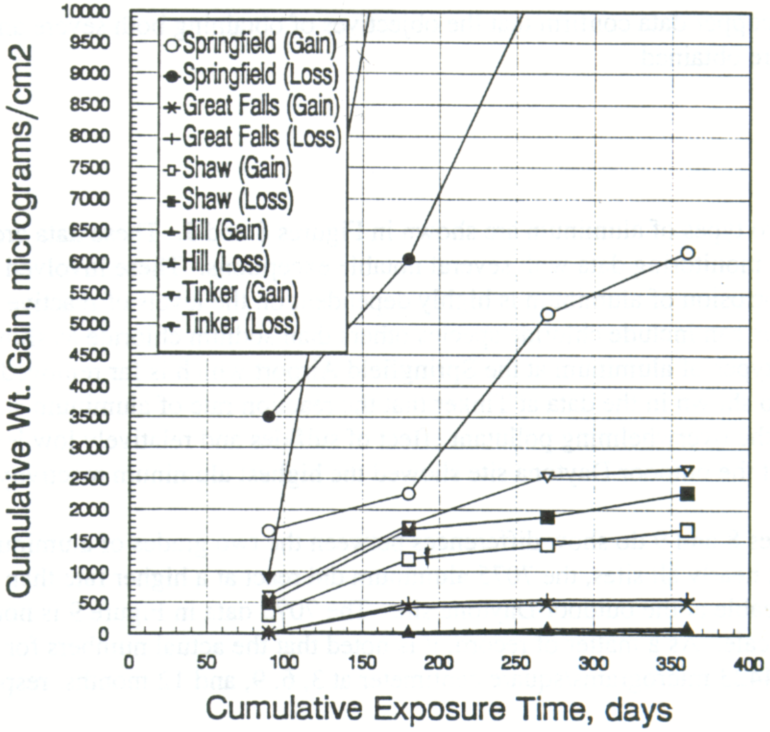

Figure 13. Comparison of weight gain and weight loss for 1010 steel at connector test sites; 12/94-12/95

Field Connector Performance

The large body of data obtained for all exposures time at all sites would be difficult to present in a concise manner in the text of this report. Therefore, in the text, selected 1-year data will be presented to illustrate significant conclusions. Additional data in the same format will be included in an Appendix section of this report.

Overall Performance, Mated Connectors

In order to introduce the field results and to indicate the rate at which degradation can occur at these field sites, the following analysis was made. For each measurement period, all data for all lubricated and mated samples were grouped together, i.e., no distinction was yet made among the various lubricants. These results are shown in Figure 14.

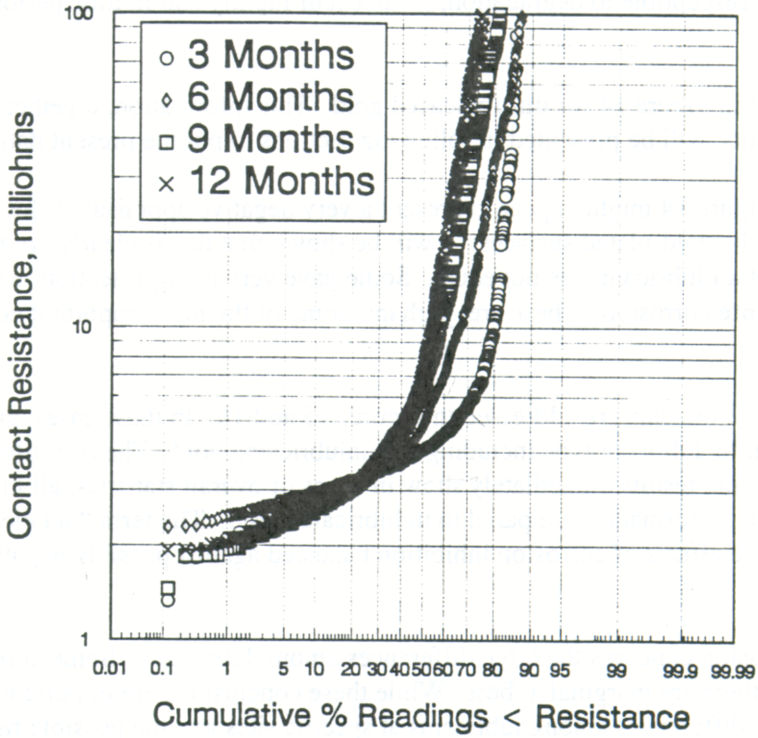

Figure 14. Contact resistance of mated gold-plated connectors exposed at all field sites; 12/94-12/95

Experience has shown that it is usually difficult for a reader who is not intimately familiar with work of this type to interpret the full significance of data such as those shown in Figure 14. Therefore, a few words of explanation are in order. Reference might first be made back to Figures 4 and 5 in which the initial data distributions are shown in the same format. Those data have two important characteristics. First, all values are low (typically < 10 milliohms) and show distributions which plot as nearly straight lines. These features are characteristics of interfaces which have **not** degraded and for which the conduction mechanism is metallic.

The second, and most important feature involves departures from the favorable distribution just described with the formation of **high resistance "tails"** as shown in Figure 14. This feature is an immediate indicator that unfavorable degradation such as corrosion has occurred. The severity of degradation is normally measured by the percentage of the sample population in the high resistance tail. This value is a more significant indicator of degradation or risk than the exact magnitude of the contact resistance change values. The basis for this conclusion will not be apparent to many readers. However, it may be summarized as follows. When a contact interface has degraded to an extent that contact resistance change exceeding even 5-10 milliohms can be measured, there is a high **probability** that in the next instant some small percentage of contacts in that population may assume almost any value of resistance including total circuit OPENS. In this respect, the measured value of high resistance is of relatively little importance compared to the fact that the resistance has increased significantly. It may also be noted that this discussion also provides the basis for the intermittent contact, failure without warning, CND's, etc.

The high resistance tails immediately indicate that a high level of degradation did occur and on a very significant portion of the population. This is the first item of significance in Figure 14 and confirms that many of the sites were indeed corrosive. The second item of importance is the statement concerning the rate at which degradation can occur. This is of considerable practical importance. The results indicate that if components are susceptible to degradation, it can occur rapidly and in time periods measured in months rather than years.

No data are shown in Figure 14 for **unlubricated** gold. This information, together with data separated among the lubricants, will be presented in following sections to put the present data in proper perspective.

A first glance at Figure 14 might appear to present a very negative appraisal of the ability of lubricants in general to protect the gold-plated surfaces. It will be shown that this is clearly not the case. However, data will also show that all lubricants are not equal. Some gave very poor protection, while a few actually appeared to **promote** corrosion. These are, perhaps, some of the most important conclusions from this program.

The latter features in the data are addressed in Figures 15 and 16. In these cases, all 1-year data for all sites together are shown by lubricant type including the unlubricated gold. These results lead to very important conclusions. First, the results immediately show in terms of overall statistics, all lubricants had a net beneficial effect on performance compared to unlubricated gold. The term "net electrical performance" refers to the positive effects of corrosion inhibition balanced against possibly negative effects due to dust collection.

The second conclusion concerns the large differences among lubricants. Some appear to be highly beneficial while others are marginal at best. While these conclusions are important, they actually understate the true differences among lubricants at specific sites and the possible risk associated with the use of **some** materials.

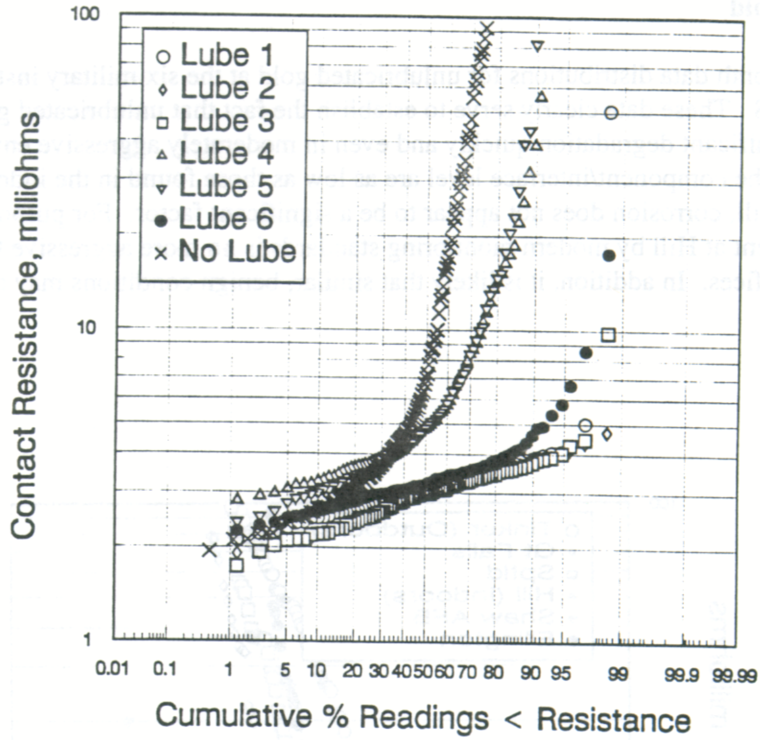

Figure 15. Contact resistance of mated gold-plated connectors exposed at all field sites; 12/94-12/95

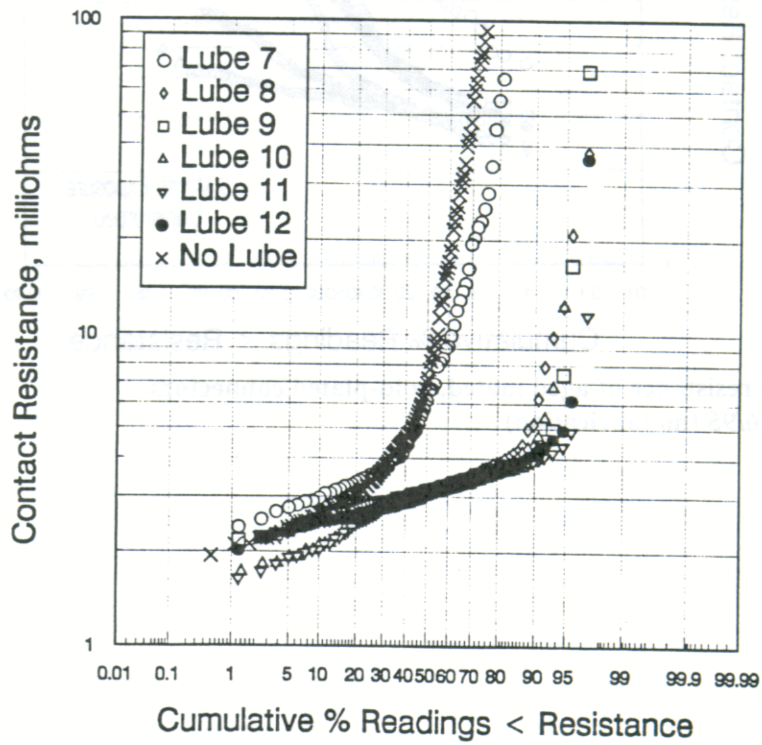

Figure 16. Contact resistance of mated gold-plated connectors exposed at all field sites; 12/94-12/95

Unlubricated Gold

The 6- and 12-month data distributions for unlubricated gold at the six military installations are shown in Figures 17 and 18. These data clearly serve to establish the fact that unlubricated gold-plated connectors may undergo significant degradation quickly and even in moderately aggressive environments. Only when environments at the component/interface level are as low as those found in the indoor, ground-based environment at Hill, corrosion does not appear to be a significant factor. For purposes of orientation, the indoor environment at Hill by modern monitoring standards is no more aggressive than environments found in many offices. In addition, it is likely that similar, benign conditions may exist within <u>some</u> well sealed LRU's.

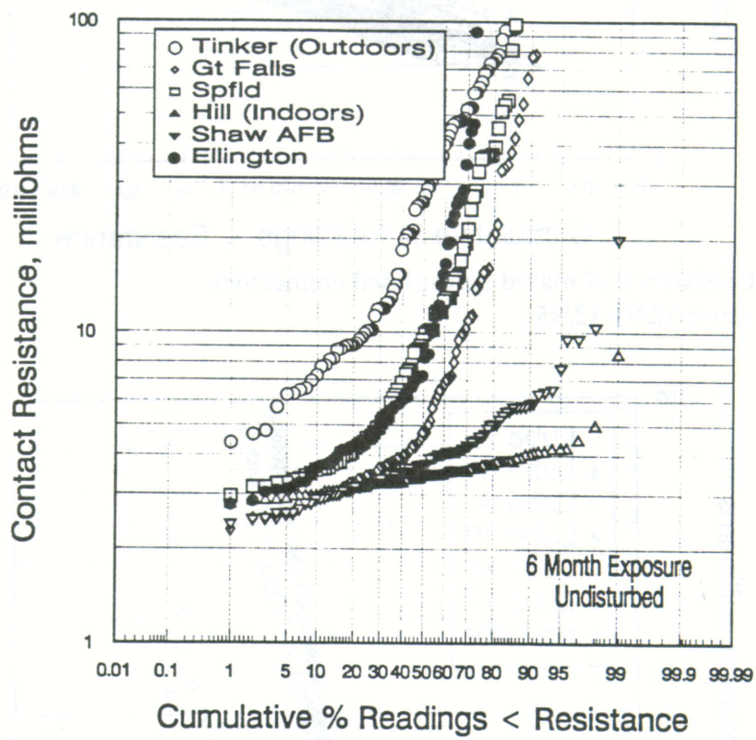

Figure 17. Contact resistance of aged mated, gold-plated connectors at field sites; 12/94-6/95 (no lubrication)

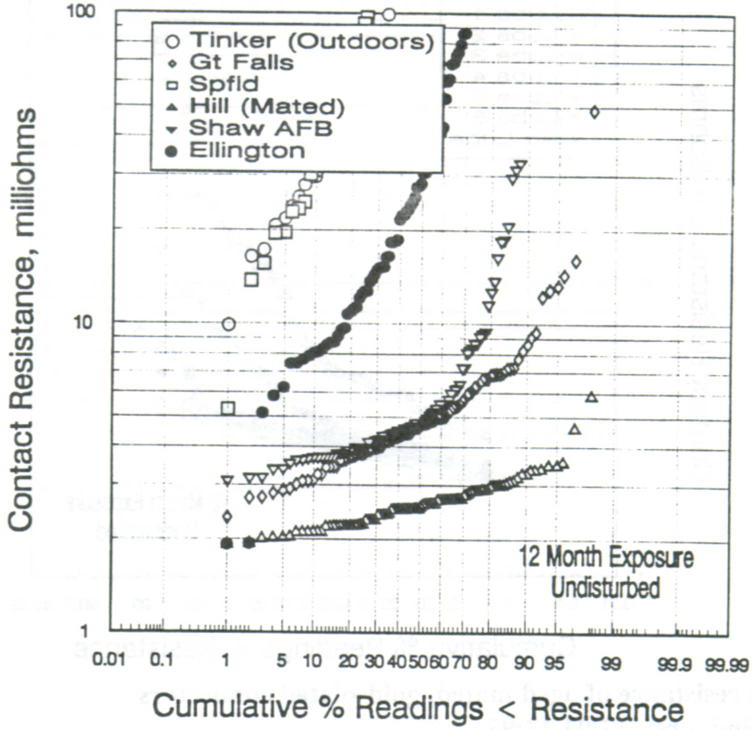

Figure 18. Contact resistance of aged mated, gold-plated connectors at field sites; 12/94-12/95 (no lubrication)

Lubricant Performance by Site

Daytona Beach, Indoors. Figures 19 through 22 show some of the most important site data obtained in this program. The reason for this is that the measured reactivity levels at Daytona are comparable to the levels which Battelle has monitored by similar techniques in the avionics areas of the A-7 and more recently the F-16 aircraft.

At these reactivity levels, the mated, unlubricated gold connectors were just beginning to degrade at the 1-year point. More important, however, was the finding of an apparent **increase** in degradation in four of the lubricated samples compared to unlubricated gold. These were Lubricants 3, 4, 5, and 7. It is believed that these effects are almost entirely due to corrosion as opposed to dust effects. These negative results, particularly for Lubricants, 4, 5, and 7 will be shown in other data including those on the lubricated steel sensors.

Figures 21 and 22 show data for one of the few sites at which long duration unmated exposures were made. These results show the expected and dramatic increase in the corrosion rate which can occur on unmated gold connectors compared to the mated condition. The degradation shown for the unlubricated gold is believed to be due almost entirely to pore corrosion which, in fact, was visible on the samples at the 12-month point. Most lubricants gave a net positive benefit compared to unlubricated gold. However, some degradation was apparent on most samples. In these cases, the dominant degradation mechanism was believed to be dust collection and retention on the lubricated surfaces. This is a clear demonstration of one of the few risk factors which may be associated with the use of lubricants. However, this may be an artificially severe test, since it is unlikely that many connectors in military applications would experience significant durations of unmated exposures, particularly without some form of protective cover.

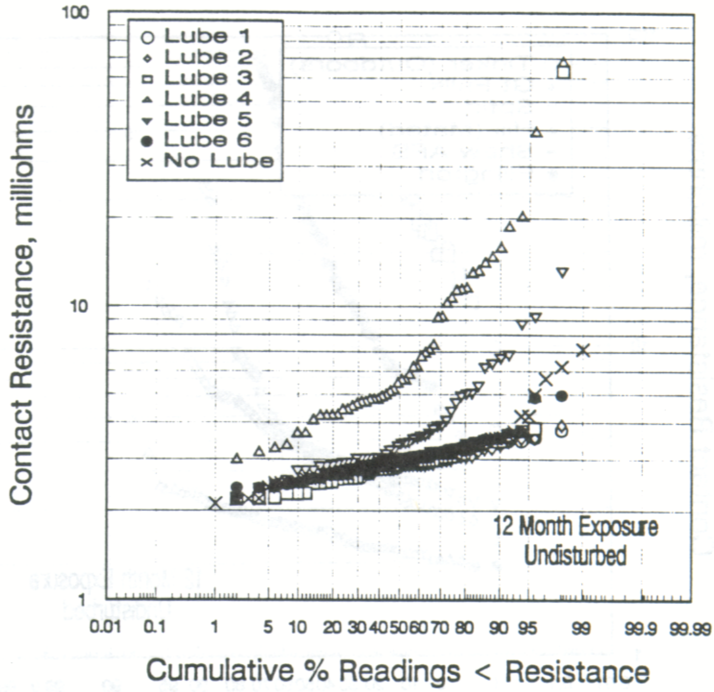

Figure 19. Contact resistance of aged mated, gold-plated connectors at Daytona Beach (indoors); 12/94-12/95

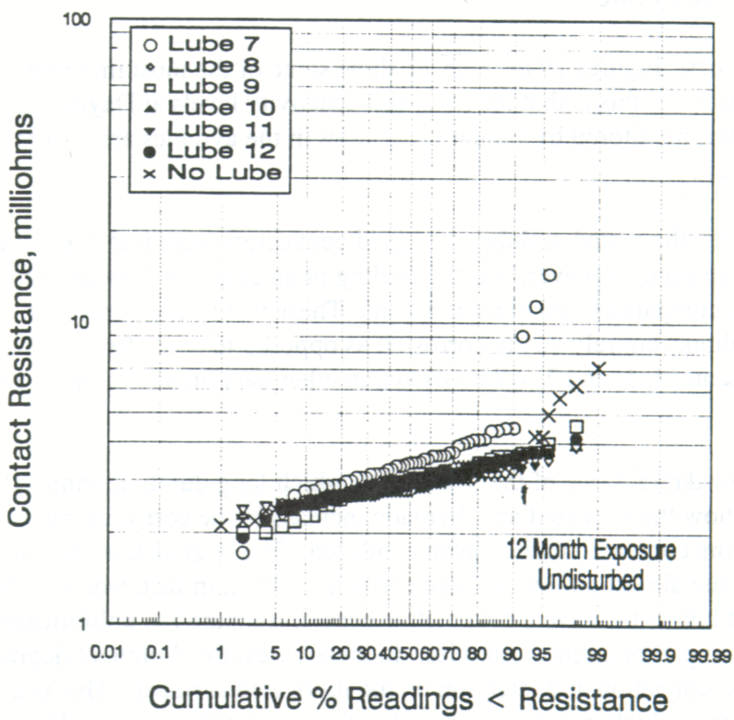

Figure 20. Contact resistance of aged mated, gold-plated connectors at Daytona Beach (indoors); 12/94-12/95

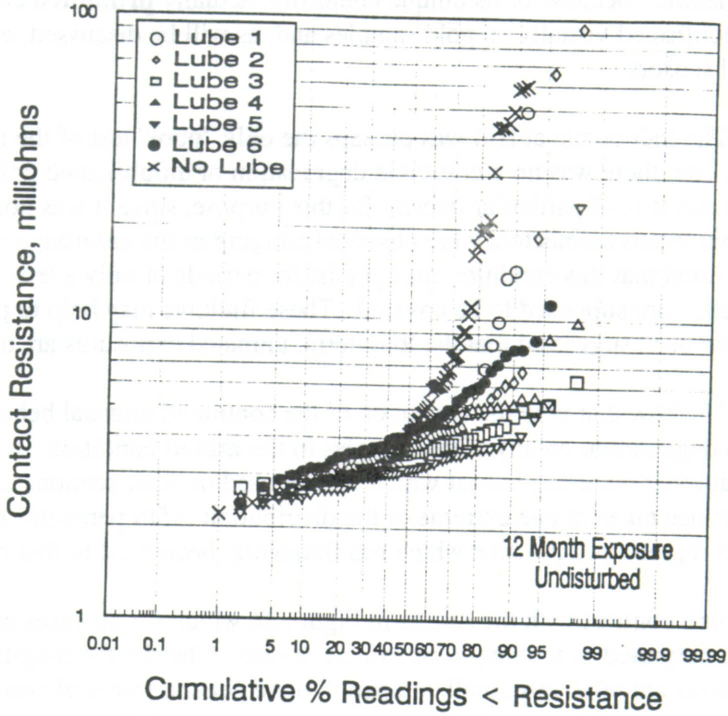

Figure 21. Contact resistance of unmated, gold-plated connectors at Daytona Beach (indoors); 12/94-12/95

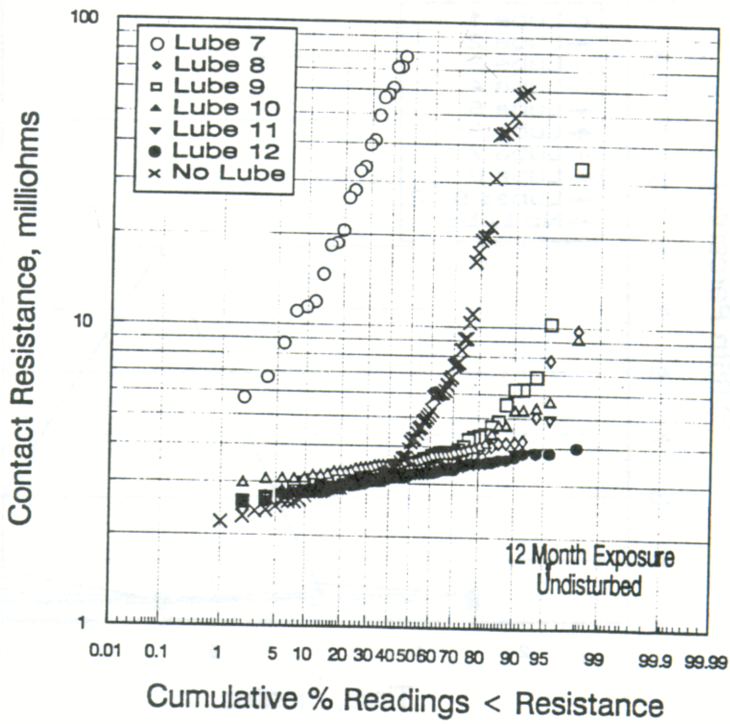

Figure 22. Contact resistance of unmated, gold-plated connectors at Daytona Beach (indoors); 12/94/12/95

The exception to the preceding statement is shown in Figure 22 for Lubricant 7. There were clear indications that this material, because of its unique chemistry, actually **promoted** corrosion on porous gold. This could be confirmed visually on gold samples and, as will be discussed, could even be observed on the lubricated steel sensors.

Hill AFB, Indoors. The indoor site at Hill was perhaps the only "pure" test of the interactions of dust and lubricant, since at this site, there was no measurable degradation of unlubricated gold due to corrosion. This site was selected and was of particular interest for this purpose, since it was noted that during the aircraft repair cycle, numerous connectors were observed hanging in the environment in the unmated condition. It is understood that this condition may persist for periods of only a few weeks, and that during this period the connectors are supposed to be covered. These findings may help to put the data in proper perspective, since it has been suggested that the long-term, unmated exposures are unrealistically severe.

The results in Figure 23 show that with the exception of the continued unusual behavior of Lubricant 7, there was virtually no degradation on any of the samples in the **mated** condition. It should be noted that Figure 23 represents another reporting format which will be used in other sections of this report. In this case, the contact resistance taken at one extreme of the distribution (95th percentile) has been plotted as a function of time. This represents a practice which has frequently been used in this type of work.

These results are in sharp contrast with the results in Figure 24 which for all cases other than possibly Lubricant 7, must be interpreted as the long-term effects of dust. Clearly, the long-term effects of dust are real. Although the effects are relatively small compared to the general threat of corrosion in more aggressive environments, the effects must be considered for any extended exposure of unmated connectors.

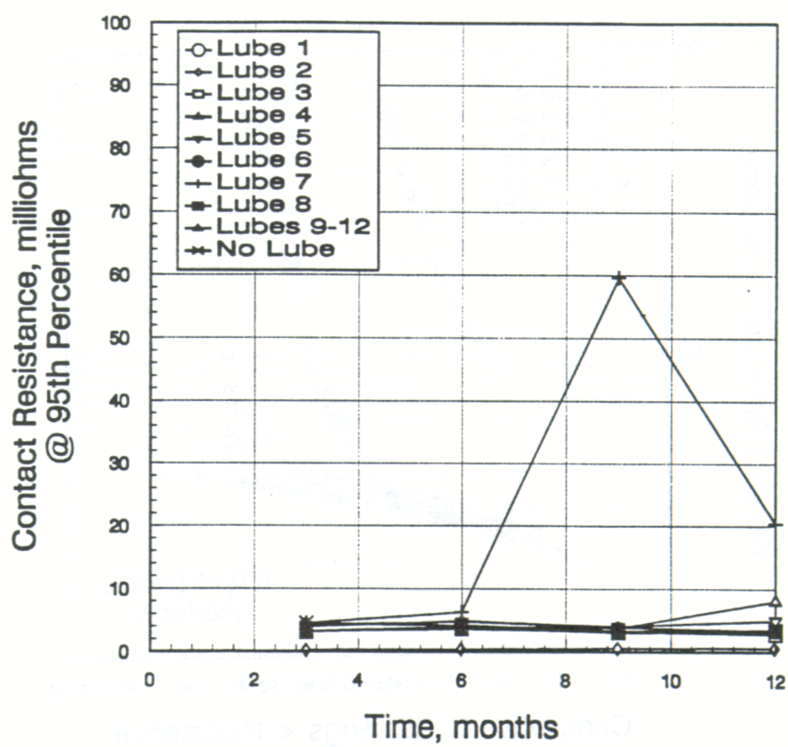

Figure 23. Contact resistance of aged mated, gold-plated connectors at Daytona Beach (indoors); 12/94-12/95

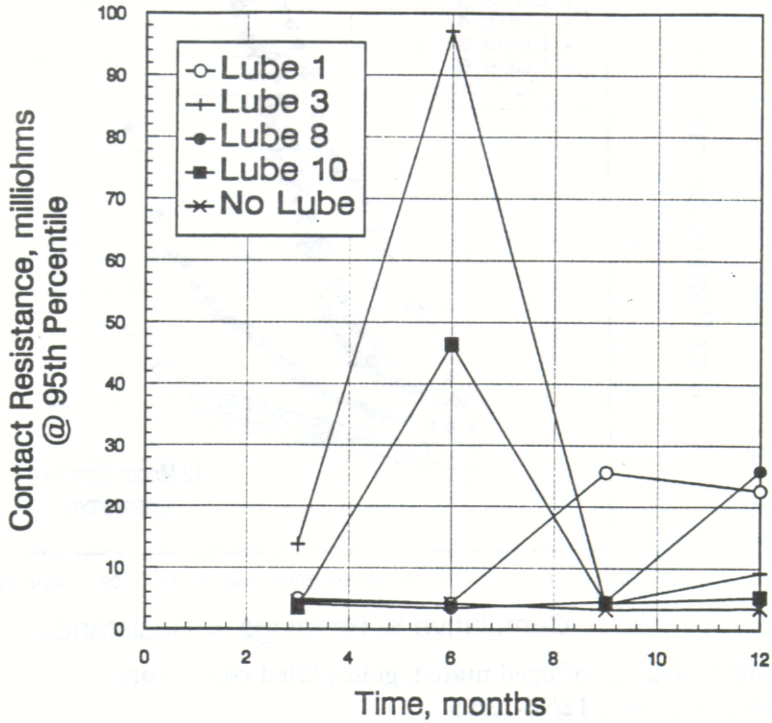

Figure 24. Contact resistance of aged unmated; gold-plated connectors at Hill AFB (indoors); 12/94-12/95

Daytona Beach, Outdoors. Results for the most severe site are shown in Figures 25 through 27. The results confirm not only the severe (and rapid) degradation of unlubricated gold, they also confirm the poor performance and apparent acceleration of corrosion for Lubricants 4, 5, and 7. All other lubricants provided a measurable beneficial effect, but again, large differences among the lubricants were found.

It was considered somewhat remarkable that any material combinations would survive long-duration exposures under these severe conditions. The fact that some did is a strong statement of the corrosion inhibiting ability of a few of the lubricants. Those lubricants which were considered to have given excellent performance in the Daytona Beach outdoor site are identified in Figure 27 in which the contact resistance (95th percentile) is plotted as a function of time.

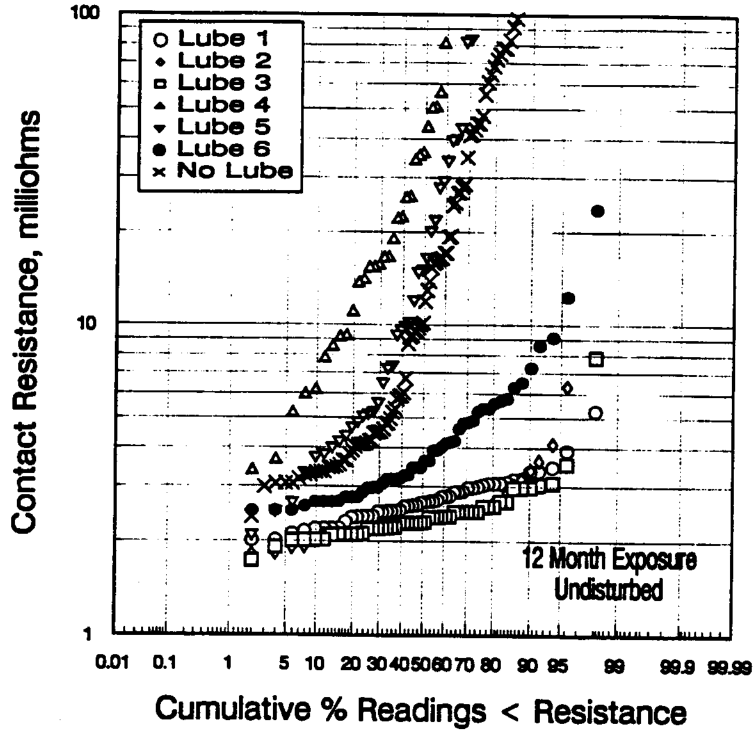

Figure 25. Contact resistance of aged mated, gold-plated connectors at Daytona Beach (outdoors); 12/94-12/95

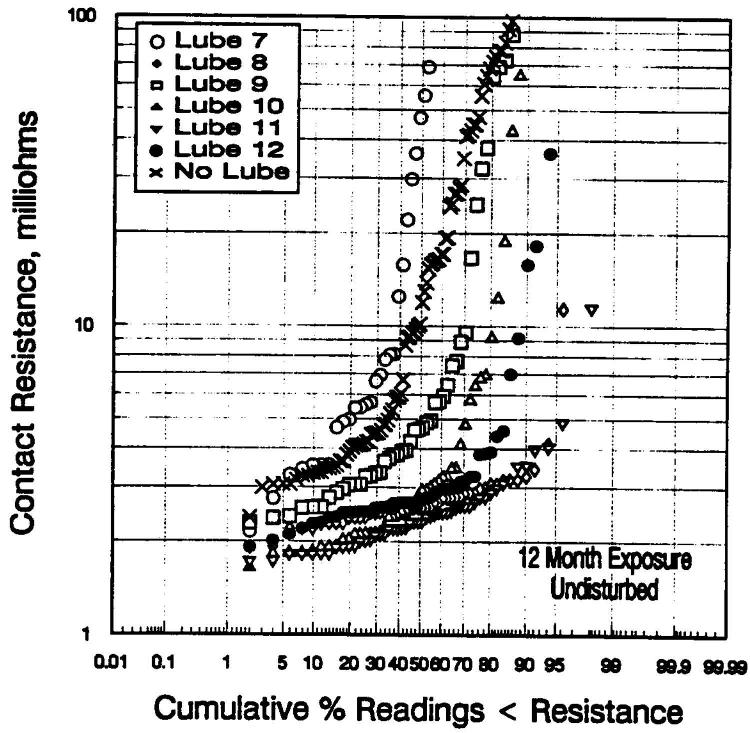

Figure 26. Contact resistance of aged mated, gold-plated connectors at Daytona Beach (outdoors); 12/94-12/95

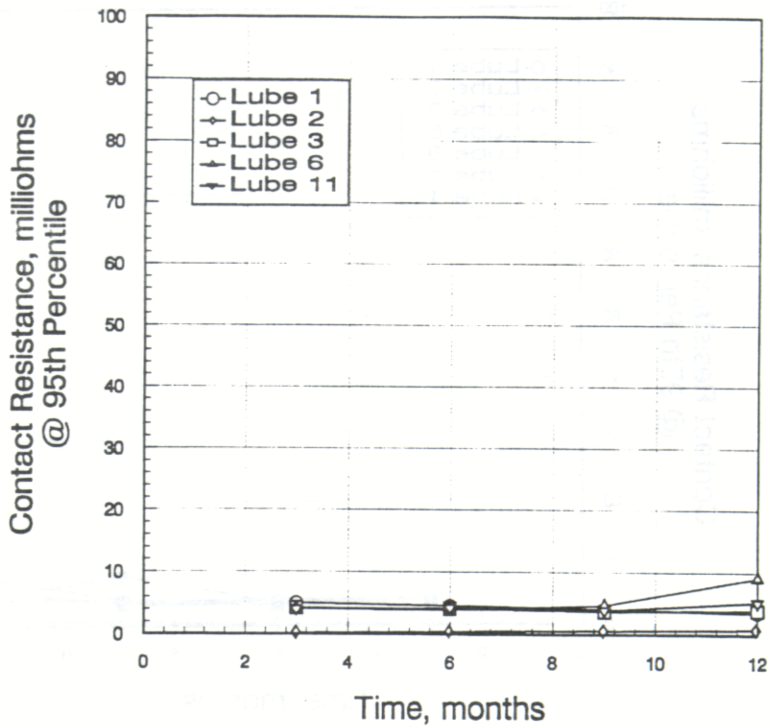

Figure 27. Contact resistance of aged mated, gold-plated connectors at Daytona Beach (outdoors); 12/94-12/95

Other Sites

Data for the remaining sites are shown in Figures 28 through 32. In each case, the data plotted are reflected in the legend for only those lubricants which were considered to have given good performance. Conversely, if lubricants are not included in the legend, they are considered to have "failed"/developed very high resistance.

These graphs have been presented in order of decreasing site reactivity. There is a general tendency in the data for an increasing number of lubricants to offer good performance as site reactivity decreases. This is not a surprising result, but it again emphasizes the conclusion that great differences exist among these materials in corrosion inhibiting ability.

These results are summarized in Table 4. This presents a concise summary of which lubricants gave the best performance at which sites. From this single table, two important conclusions can be reached. First, only three Lubricants (1, 2, and 6) performed well under all field conditions. Second, all lubricants except possibly No. 7 performed well at the most benign site (Hill, indoors). While this result is not surprising, it is of little significance, since corrosion did not occur even on unlubricated gold at such a low reactivity level. At a minimum, the Hill results did indicate that for mated connectors with lubricant, there did not appear to be any adverse effect of dust collection on performance.

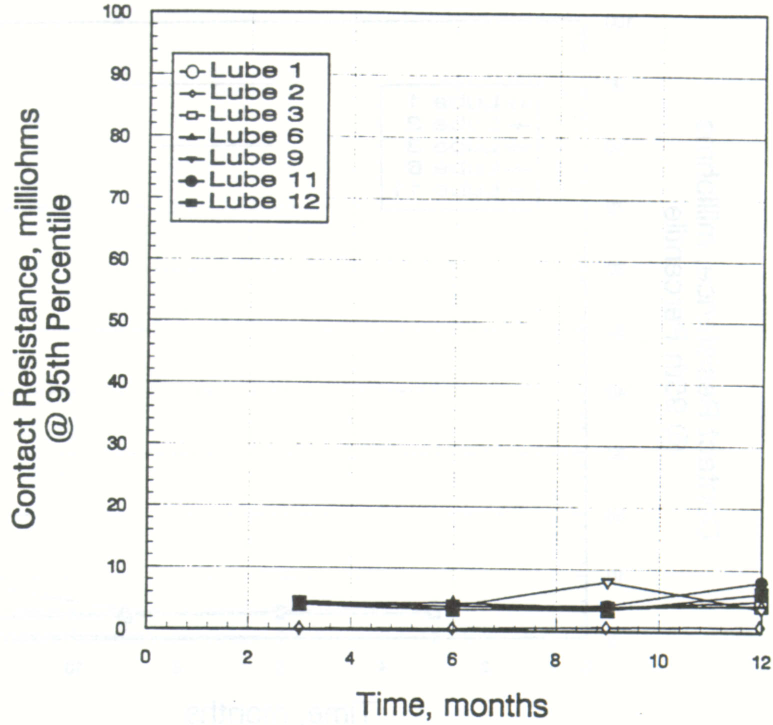

Figure 28. Contact resistance of aged mated, gold-plated connectors at Tinker AFB (outdoors); 12/94-12/95

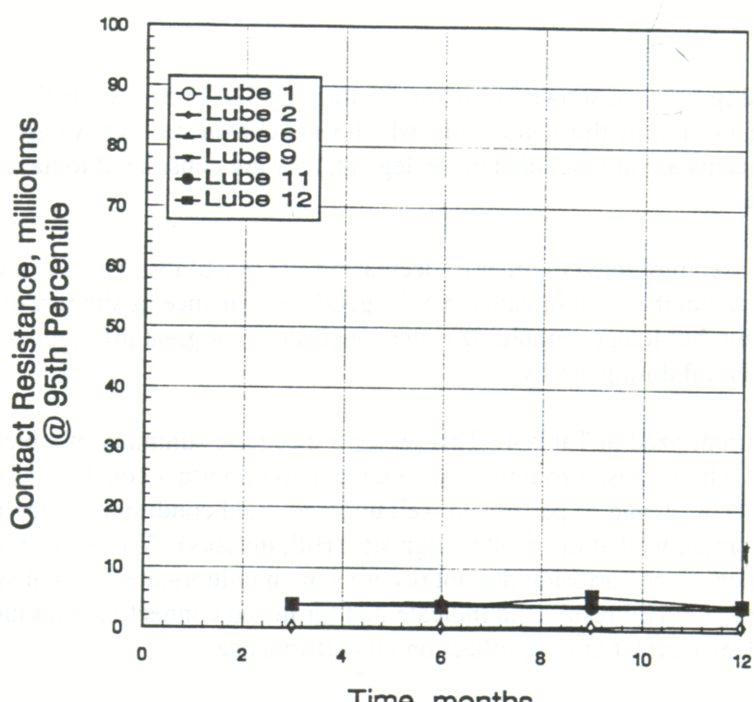

Figure 29. Contact resistance of aged mated, gold-plated connectors at Springfield (outdoors) 12/94-12/95

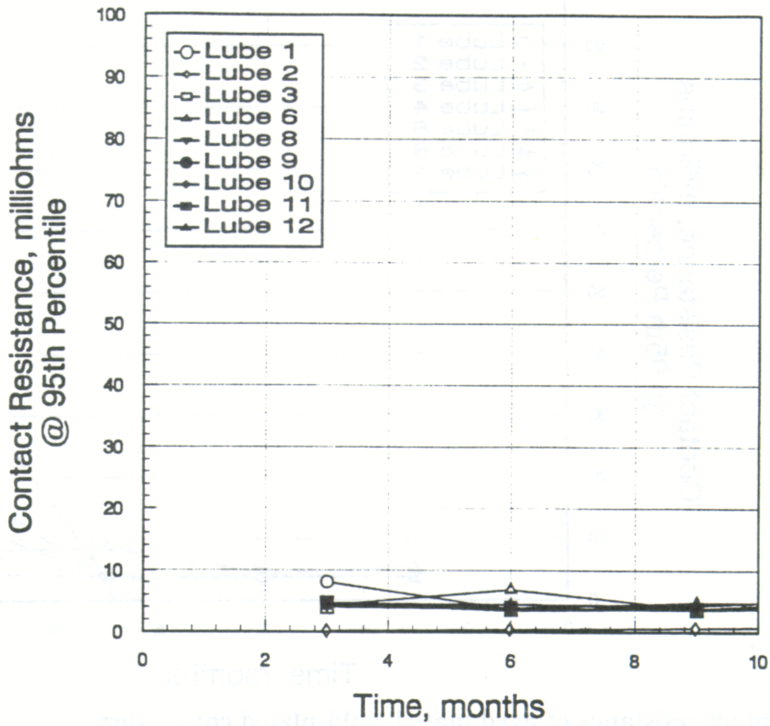

Figure 30. Contact resistance of aged mated, gold-plated connectors at Ellington; 12/94-12/95

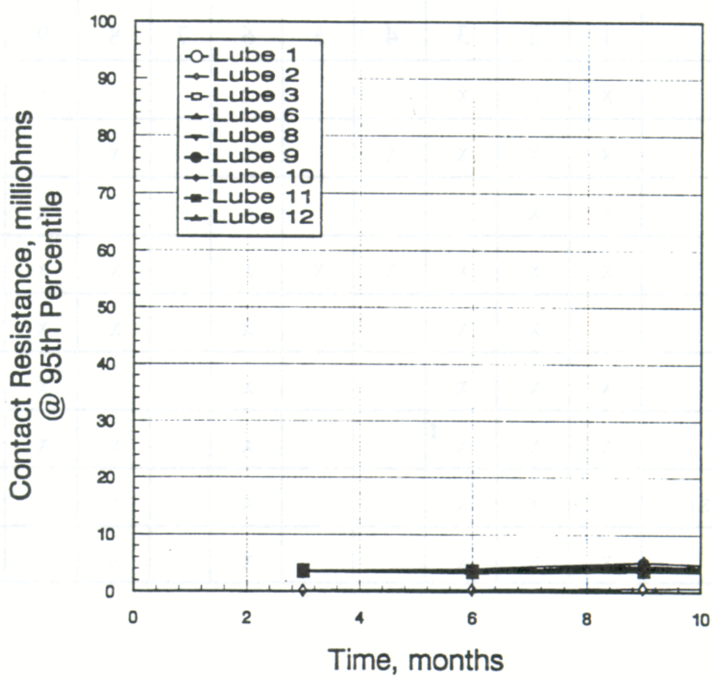

Figure 31. Contact resistance of aged mated, gold-plated connectors at Shaw AFB (outdoors); 12/94-12/95

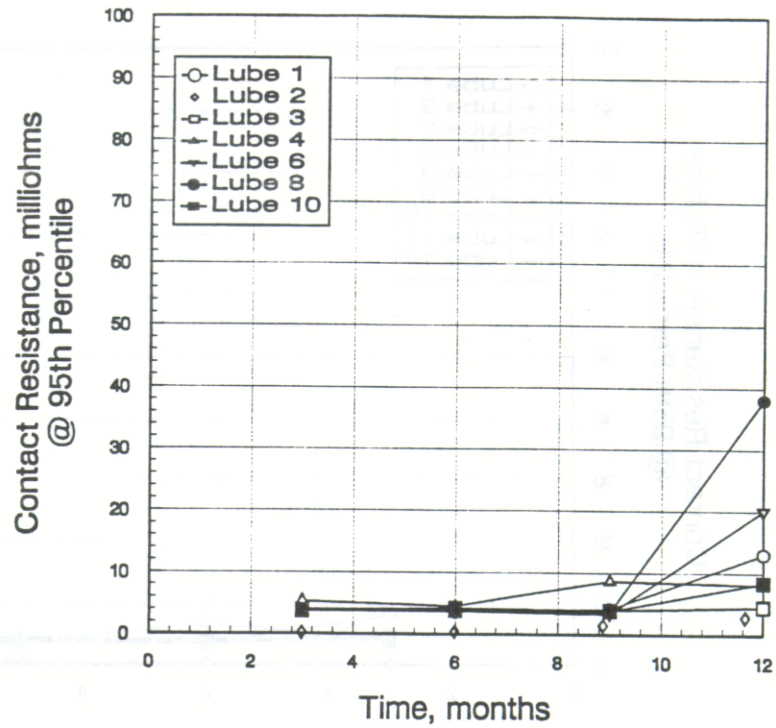

Figure 32. Contact resistance of aged mated, gold-plated connectors at Great Falls; 12/94-12/95

Table 4. Summary of lubricants showing good performance during 1-year field exposures; mated

	1	2	3	4	5	6	7	8	9	10	11	12	No Lube
Tinker (outdoor)	x	x	x			x			x		x	x	
Gt Falls	x	x	x	x		x		x		x			
Springfield	x	x				x			x		x	x	
Hill (indoors)	x	x	x	x	x	x		x	x	x	x	x	x
Shaw	x	x	x			x		x	x	x	x	x	
Ellington	x	x	x			x		x	x	x	x	x	
Daytona (indoors)	x	x	x			x		x	x	x	x	x	
Daytona (outdoors)	x	x	x			x		x			x		
Tinker (indoors)	x	x	x			x		x					

Lubricants 1, 2, and 6. Detailed data are shown by site for the three lubricants which were considered to show the best performance at all sites studied in this program. All of these materials are considered to have shown good performance, particularly with respect to the high level of degradation observed on unlubricated gold.

Special mention should be made of the data obtained on Lubricant 1 at Great Falls. These results appear to show a sharp resistance tail at the 12-month point in spite of the fact that the Great Falls site was relatively benign.

An unusual event occurred at this location sometime between the 9-and 12-month measurement points. This event was associated with what was reported to be near-hurricane force winds. Several of the test cards were dislodged from the rack and subjected to unusually high levels of dust and dirt together with unknown levels of abuse by the elements. It is known that the Lubricant 1 test card was among this group. Therefore, the results shown in Figure 33 are believed to be due almost exclusively to artificially high levels of dirt. The results are, therefore, not representative of the general behavior of the samples at this location. This conclusion is supported, in part, by the finding that there was no measurable degradation on the same sample after exposures of 3, 6, and 9 months.

Similar results are shown in Figure 35 for Lubricant 6 at the same location. Exactly the same problem was found, and it was also observed that there was no degradation on the Lubricant 6 sample through 9 months of exposure.

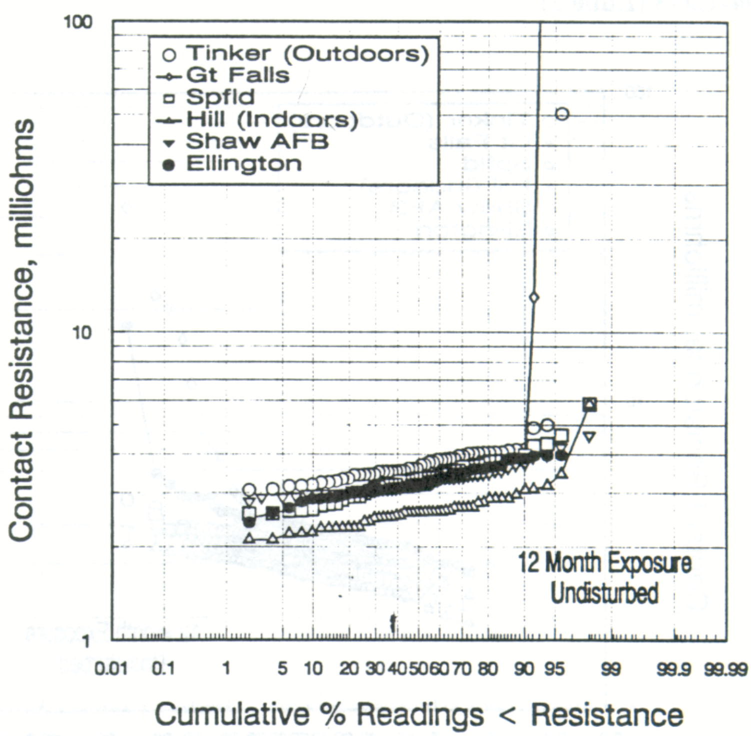

Figure 33. Contact resistance of aged mated, gold-plated connectors at field sites; 12/94-12/95 (Lube 1)

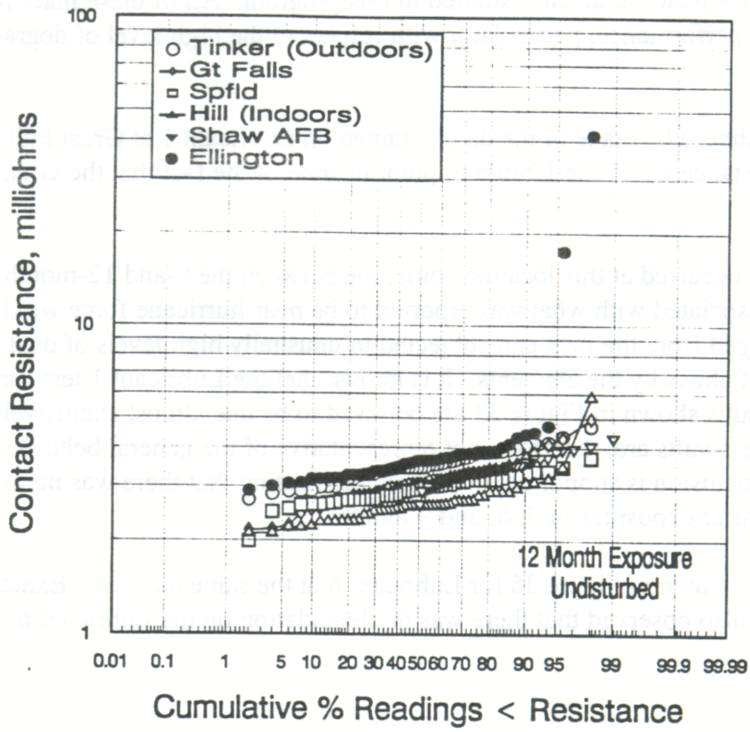

Figure 34. Contact resistance of aged mated, gold-plated connectors at field sites; 12/94-12/95 (Lube 2)

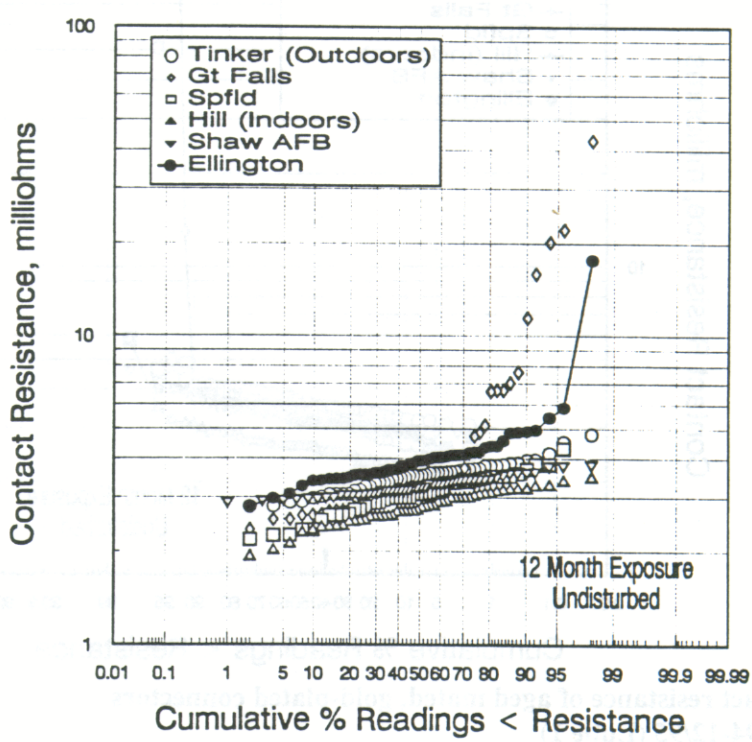

Figure 35. Contact resistance of aged mated, gold-plated connectors at field sites; 12/94-12/95 (Lube 6)

Lubricant 7 Results. The Lubricant 7 data were so consistently negative that special mention should be made of the effects which an improperly qualified lubricant can have. These data are shown in Figure 36. Although the 1-year data have been presented for comparison to the previous data, it may be mentioned that degradation on the Lubricant 7 samples was found within the 3 months of exposure.

It has been concluded that the effects shown in Figure 36 are corrosion related. It is further believed that the results are due to an affinity of this particular lubricant for water vapor. This is in sharp contrast to most, if not all, of the other lubricants which are believed to be hydraphobic.

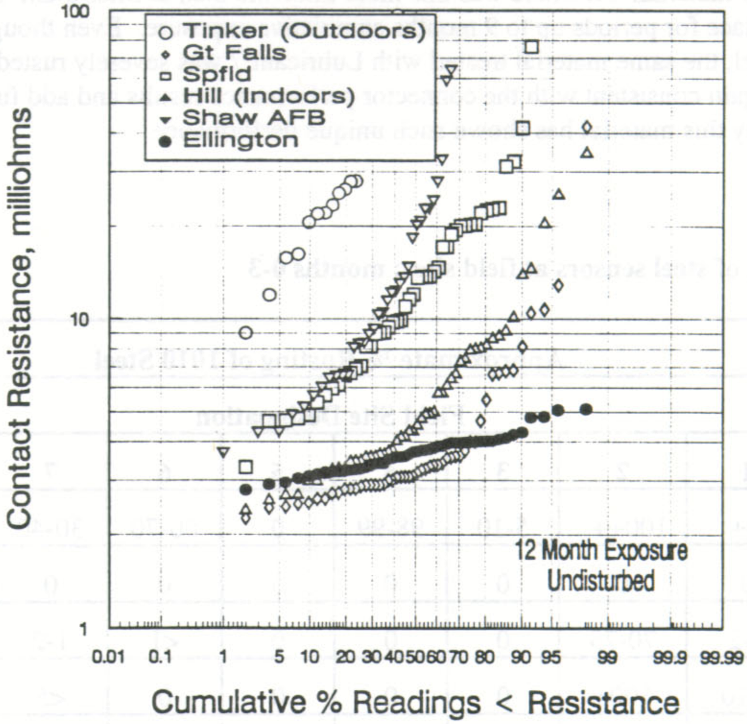

Figure 36. Contact resistance of aged mated, gold-plated connectors at field sites; 12/94-12/95 (Lube 7)

Steel Sensors

The lubricated steel sensors proved to be very effective in demonstrating the corrosion inhibiting ability of some of these lubricants. The reverse was also true.

Data are shown in Tables 5 through 8 for visual estimates of the percent area which was rusted on each sample for each 3-month exposure period. These data are always compared to unlubricated steel as indicated by the designation "Lube 0".

Particular attention should be drawn to two features in the data. The first involves the performance of Lubricants 1, 2, and 6 at all sites. It is clear that these three lubricants were somewhat unique in consistently providing nearly total corrosion protection for this very sensitive material for periods of at least 3 months. Significant protection was achieved even in the outdoor seacoast environment of Site 2.

If the results for Site 2 are excluded from the data, it is clear that a number of the other 81309 lubricants did provide significant protection for steel at a number of locations. The exceptions to this are Lubricants 4 and 5 which consistently gave rather poor performance. In spite of these latter conclusions, the data still appear to show that Lubricants 1, 2, and 6 were unmatched in terms of protection and consistency of results at all sites.

It is again noted that these results are in direct agreement with the connector performance results. This provides added support to the conclusion that the use of simple materials such as steel may provide a very effective means for lubricant screening in the future.

The second feature in the data concern the performance of Lubricant 7, particularly in comparison to the results for unlubricated steel. These results clearly indicate that at many sites, the corrosion of steel was accelerated by this material. Nowhere was this more dramatic than at Sites 5 and 6 where separate samples had been left in place for periods up to 9 months cumulative exposure. Even though visual rusting was not found on bare steel, the same material treated with Lubricant 7 was severely rusted. These results for Lubricant 7 are again consistent with the connector performance results and add further support to the explanation of why this material has shown such unique performance.

Table 5. Corrosion of steel sensors at field sites; months 0-3

Approximate % Rusting of 1010 Steel									
Field Site Designation									
Lube	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	100+	100++	5-10	98-99	0	60-70	30-40	70-80	40-50
1	0	0	0	0	0	0	0	0	0
2	1-2	70-75	0	0	0	<1	1-2	0	0
3	5-10	100+	0	0	0	0	<5	0	0
4	60-70	100+	0	1-2	0	20-30	10-15	<5	0
5	30-40	100+	0	2-5	0	20-30	10-15	<5	0
6	1-2	60-70	0	0	0	0	0	0	0
7	100++	100+	15-20	100+	2-5	80-90	50-60	90-95	80-90
8	0	15-20	0	0	0	<1	1-2	0	0
9	5-10	100+	0	5	0	<1	0	0	0
10	1-2	20-30	0	0	0	<1	1-2	0	0
11	0	15-20	0	0	0	<1	0	0	0
12	0	100+	0	0	0	<1	0	0	0

Table 6. Corrosion of steel sensors at field sites; months 3-6

Approximate % Rusting of 1010 Steel										
	Field Site Designation									
Lube	**1(b)**	**2**	**3(b)**	**4**	**5(b)**	**6(b)**	**7**	**8**	**9**	**10**
0	100	100++	5-10	98-99	0	0	80-90	30-40	70-80	40-50
1	0	5-10	0	0	0	0	0	0	0	0
2	<5	5-10	0	0	0	0	0	1-2	0	0
3	20-30	100	0	0	0	0	0	<5	0	0
4	(a)	90-100	0	5	0	0	5-10	5-10	<5	0
5	(a)	90-100	0	50-60	0	0	5-10	5-10	<5	0
6	0	<5	0	0	0	0	0	0	0	0
7	(a)	100+	70-80	(a)	2-5	2-5	80-90	50-60	90-95	80-90
8	0	15-20	0	0	0	0	0	0	0	0
9	20-30	90-100	0	2-5	0	0	1-2	0	0	0
10	0	20-30	0	0	0	0	<1	1-2	0	0
11	<5	10-15	0	0	0	0	<1	0	0	0
12	<5	50-60	0	0	0	0	<1	0	0	0

(a) Samples not included this period
(b) Six months cumulative exposure

Table 7. Corrosion of steel sensors at field sites; months 6-9

Approximate % Rusting of 1010 Steel										
Field Site Designation										
Lube	**1**	**2**	**3**	**4**	**5(b)**	**6(b)**	**7**	**8**	**9**	**10**
0	100	100++	5-10	100	0	0	40-50	30-40	100++	100
1	0	<5	0	0	0	0	0	0	0	0
2	0	<5	0	0	0	0	0	0	0	0
3	0	100	0	0	0	0	0	0	0	0
4	60-70	100	0	10-20	0	0	20-30	0	5-10	0
5	80-90	100	0	80-90	0	0	20-30	1-2	30-40	<5
6	0	60-70	0	0	0	0	0	0	0	0
7	(a)	100++	70-80	(a)	80-90	80-90	(a)	(a)	(a)	(a)
8	<5	10-15	0	0	0	0	0	0	0	0
9	60-70	80-90	0	20-30	0	0	0	0	<5	0
10	10-15	5-10	0	0	0	0	0	0	0	0
11	10-15	15-20	0	10-20	0	0	0	0	25-30	0
12	10-15	30-40	0	40-50	0	0	0	0	0	0

(a) Samples not included this period
(b) Nine months cumulative exposure

Table 8. Corrosion of steel sensors at field sites; months 9-12

Approximate % Rusting of 1010 Steel										
	Field Site Designation									
Site	**1**	**2**	**3(b)**	**4**	**5(c)**	**6(c)**	**7**	**8**	**9(d)**	**10**
0	100	100++	80-90	95	0	0	15-20	30-40	5-10	
1	0	30-40	0	0	0	0	0	0	0	
2	0	30-40	0	0	0	0	0	0	0	
3	0	70-80	0	0	0	0	0	0	0	
4	0	100	0	10-20	0	0	0	0	<5	
5	5-10	100	<5	60-70	0	0	0	0	<5	
6	0	70-80	0	0	0	0	0	0	0	
7	(a)	(a)	100	(a)	100	100	(a)	(a)	(a)	(a)
8	0	10-15	0	0	0	0	0	0	0	
9	0	80-90	0	<5	0	0	0	0	<5	
10	0	40-50	0	0	0	0	0	0	0	
11	0	40-50	0	0	0	0	0	0	25-30	
12	0	70-80	0	0	0	0	0	0	0	

(a) Samples not included this period
(b) Six months cumulative exposure
(c) Nine months cumulative exposure
(d) See text re significant environmental change ~ month 9

Laboratory Test Results

The purpose of the laboratory studies was to subject exactly the same types of test samples to a systematic evaluation of the effects of individual environmental variables. Emphasis in this work was placed on thermal effects involving lubricant stability in order to determine whether there were any long-term risk factors associated with lubricant property changes. Beyond this emphasis, the work was designed to evaluate corrosion inhibition under well-defined conditions.

Low Temperature Performance

In order for a lubricant to be considered acceptable for many military applications, it should be capable of continuing to perform its function at low temperatures for the intended applications in connector products. This means that lubricant properties should not change to a degree that they will interfere with the conduction process. This area was investigated, since it is known that any of these lubricants will substantially increase in vicosity or even solidify at lower temperatures. In fact, this work was increased in importance due to previous studies (2) which showed unfavorable results for many conventional lubricants at low temperatures.

Results are shown in Figures 37 and 38 for in situ measurements of contact resistance at various temperatures between 25 and -55 C. The two results shown for Lubricants 1 and 9 represent the extremes in performance which were found. If a conservative approach is adopted to consider as acceptable those lubricants showing a contact resistance increase at any point of less than 10 milliohms, materials falling

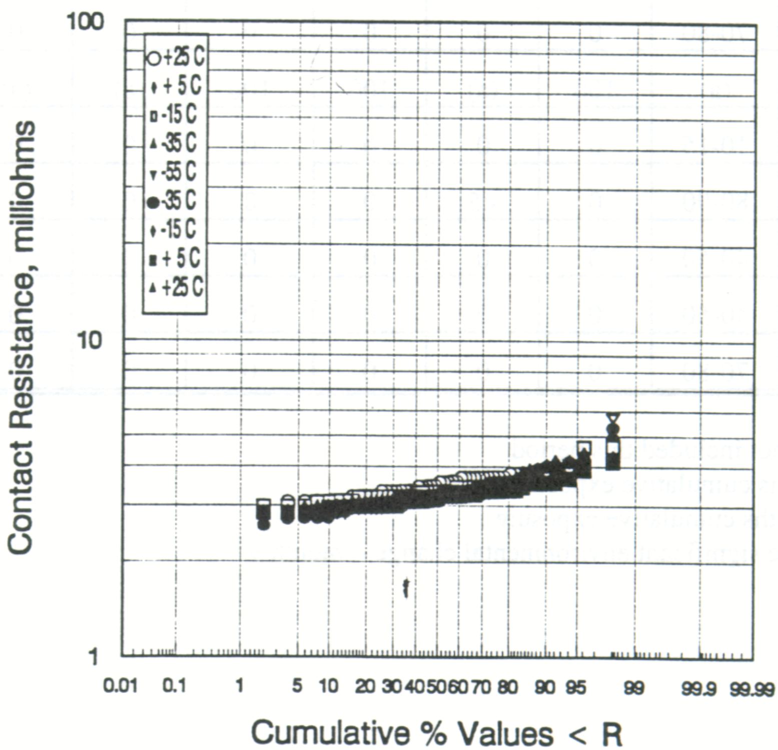

Figure 37. Contact resistance of lubricated connectors at low temperatures (+25 to -55 C); Lube 1

into the category of Lubricant 1 are entirely favorable. On the other hand, materials such as Lubricant 9 tended to show poor performance at low temperatures.

We must carefully note that the results such as those shown for Lubricant 9 do not necessarily mean that systems having this lubricant and operating at low temperatures would fail. However, the results must, at a minimum, be regarded as an increase risk of failure. Therefore, materials having the characteristics shown in Figure 37 are more desirable.

On this basis, a summary is given in Table 9 of the approximate lower temperature limits of performance for each material. Lubricants 1, 4, 6, and 8 appeared to give satisfactory performance at all temperatures. Lubricant 2 performed well at most temperatures although there were isolated high resistance readings at an intermediate value of +5 C. Lubricants 3 and 5 failed very rapidly as temperatures were decreased. These results do not imply any permanent change in lubricant properties as a result of exposures to low temperatures. In fact, the data show a close return to the same performance at all temperatures.

Finally, it is noted that the subject of low-temperature performance is not addressed in either 81309 or 87177A. It is strongly recommended that such changes be made, since these results demonstrate possibly significant risk associated with the use of some lubricants at low temperatures.

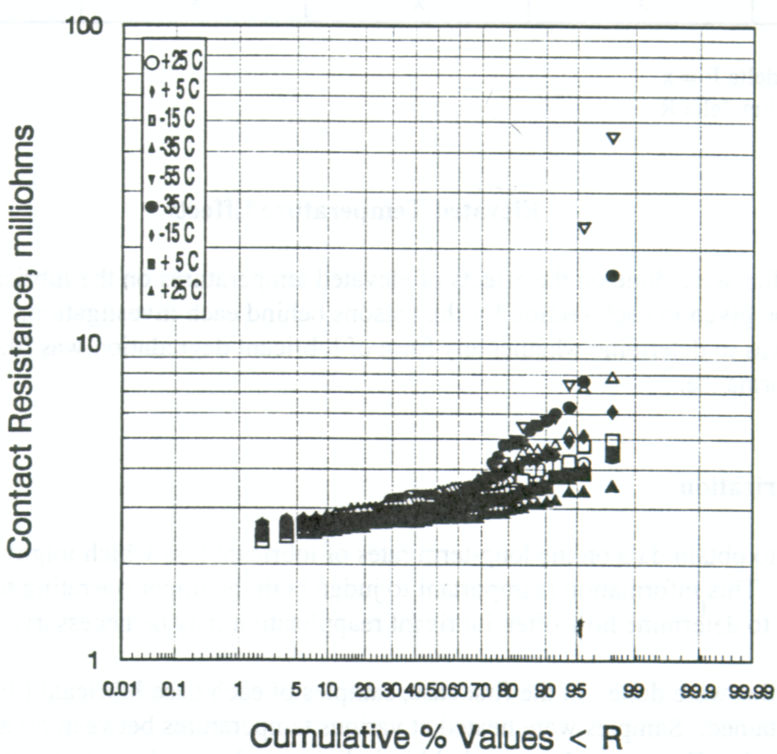

Figure 38. Contact resistance of lubricated connectors at low temperatures (+25 to -55 C); Lube 9

Table 9. Summary of low temperature performance

Lubricant	Good Performance(a) at Indicated Temperature, C				
	25	5	-15	-35	-55
1	x	x	x	x	x
2	x	--(b)	x	x	x
3	x	x	--	--	--
4	x	x	x	x	x
5	x	x	--	--	--
6	x	x	x	x	x
7	x	x	x	x	--
8	x	x	x	x	x
9	x	x	x	--	--
10	x	x	x	x	--
11	x	x	x	x	--
12	x	x	x	x	--

(a) <10 milliohms delta R = x
(b) -- = >10 milliohm delta R

Elevated Temperature Effects

A number of studies were done on the effects of elevated temperatures on the lubricants. A brief description will be given in each section for the reasons behind each investigation. The primary driving force, however, was to determine whether any form of lubricant degradation was likely to occur which could affect performance.

Lubricant Vaporization

It was of interest to obtain data on the long-term rates of lubricant loss which might be expected from metallic surfaces. This information is important to judge both the upper operating temperature limits for lubricant use and to determine how often lubricant reapplication may be necessary.

Two types of studies were done. In the first case, samples of each base lubricant (with the volatile carrier removed) was obtained. Samples were heated at various temperatures between 80 and 150 C for long periods of time in air. These samples were held in individual glass vials such that the lubricant could freely evaporate. These vials were periodically weighed, and from these data, loss rates as a function of temperature could be determined.

In the second case, samples of the gold-plated, simulated pc boards were lubricated on one side by spraying. These samples were held on their edges horizontally in individual glass bottles. These, in turn, were first equilibrated at 50 C for 24 hours to remove traces of the volatile carrier. Thereafter, they were reweighed and then individual samples were heated at several temperatures and periodically weighed to determine lubricant loss rates from an actual gold-plated surface.

Figure 39 shows all of the results for most of the lubricants presented in a conventional Arrhenius plot of vaporization rates as a function of temperature. There are several points of significance in these data. First, over the entire temperature range, the data generally follow a constant slope. The interpretation of this behavior is one of a constant activation energy indicating no apparent change in rate controlling mechanism over this temperature range. This suggests that there was no significant change in loss or degradation mechanisms. The practical significance is that elevated temperature aging over at least this temperature range should be valid.

The second point of significance is that the slope of the curves shown in Figure 39 are very similar. This provides some technical basis for conducting elevated temperature aging at constant conditions, having some assurance that the loss mechanisms are the same as those which would occur at lower service temperatures, and providing a basis for the extrapolation of elevated temperature data to lower, long-term conditions.

On the basis of the positive results just obtained, experiments were conducted to examine actual vaporization rates from lubricated gold surfaces. These results are summarized in Figures 40 and 41. It is evident that the loss rates differ significantly among the different materials.

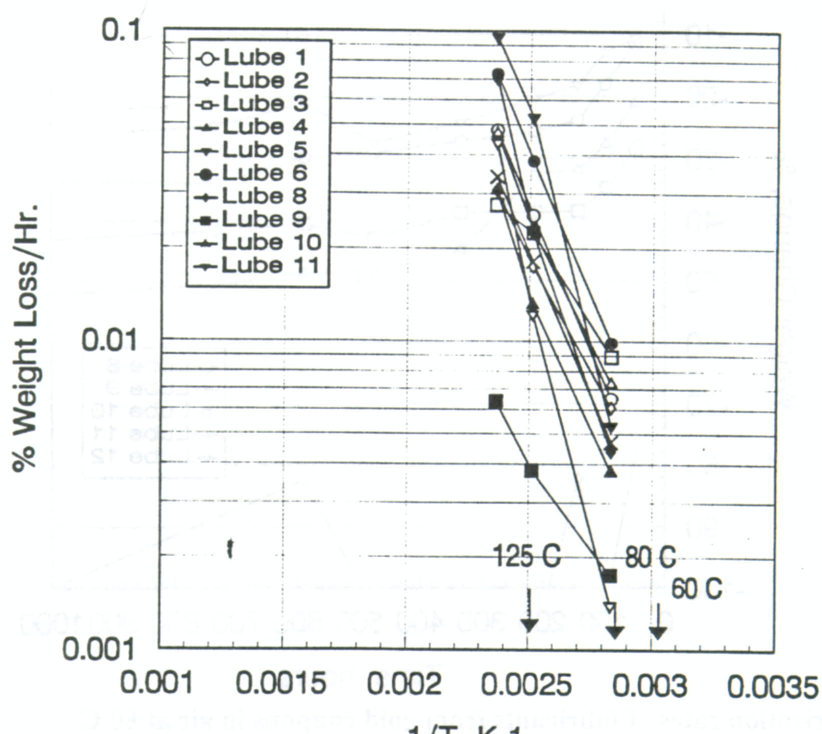

Figure 39. Arrhenius plot of vaporization rates of lubricants in air

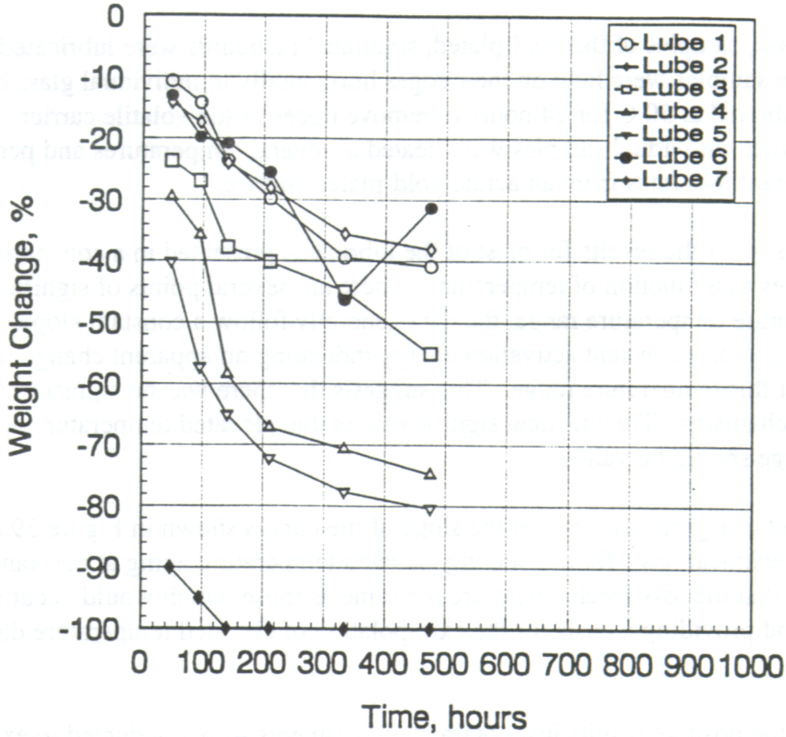

Figure 40. Vaporization rates of lubricants from gold coupons in air at 80 C

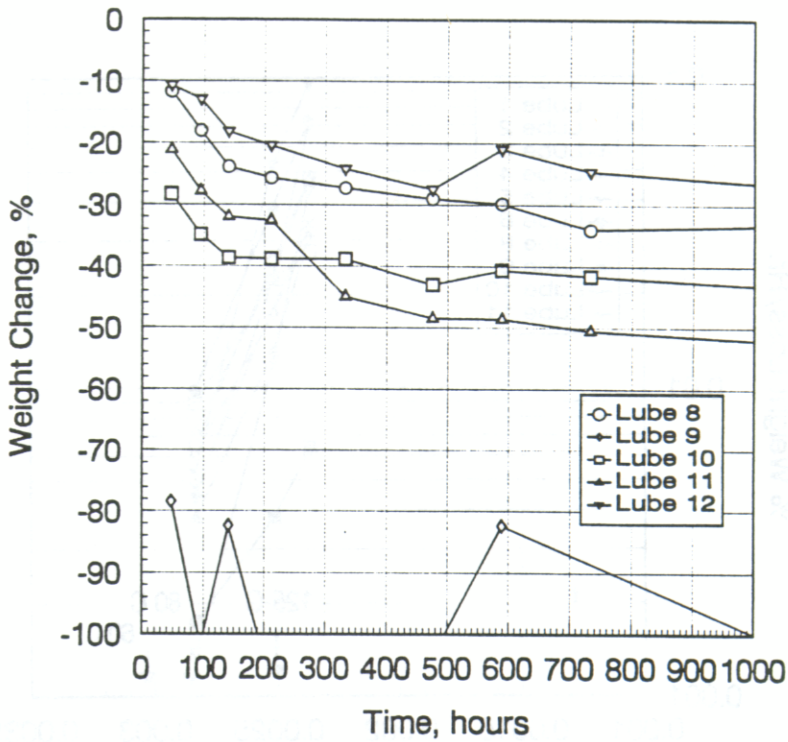

Figure 41. Vaporization rates of lubricants from gold coupons in air at 80 C

There do not exist any accepted standards for lubricant loss rates. However, discussions among some technical personnel working in this field would suggest that losses during elevated temperature aging should not exceed about 50 percent. On this basis, it may be concluded that Lubricants 1, 2, 6, 8, 10, and 12 show relatively good retention. Furthermore, it may be only coincidence that the three lubricants which exhibited best performance in field and laboratory studies also showed the lowest loss rates (Lubricants 1, 2, and 6). Conversely, some of the worst performing Lubricants (4, 5, and 7) showed very high rates of loss. This information may provide some additional support for a 50 percent minimum retention value.

The results in Figures 39 through 41 may be used for approximate calculations of the relevance of elevated temperature aging at 80 C. If it is assumed that during the entire lifetime of a component, the average operating temperature is about 40 C, aging in air at 80 C represents an acceleration of about 10:1. This means that for lubricants having the characteristics of Lubricants 1, 2, or 6, for example, all would probably require in excess of 3 years at 40 C to reach the 50 percent loss condition. These calculations are based on a worst case/overly conservative estimate of free evaporation of the lubricant. In reality, these materials are likely to be used in mated connectors where both the connector housing and forces of capillary attraction by the interfaces should greatly retard material loss.

In summary, these results indicate that in most practical applications of connector products, lubricant retention at least for the better lubricants should be high. Any requirements for relubrication due to loss by natural processes would probably be measured in years.

Thermal Aging, Coupons

In the next series of experiments, samples of the gold-plated, simulated pc boards were lubricated on both sides, then thermally aged. After the thermal aging, these samples were mated to individual and new test connectors for measurement purposes. The objective of this work was to provide a direct determination of whether there was any oxidation process which will degrade the lubricant to an extent that it may affect electrical performance.

Two aging conditions were used in the current work. These were 80 C for 1,000 hours and 125 C for 500 hours. A determination was quickly made that conditions of 125 C for 500 hours will degrade all of the systems studied in this program. The word "system" is important, since the results obtained do not necessarily indicate the degradation of the lubrication was exclusively responsible for the observed degradation. It is known that gold platings can suffer degradation at these temperatures. This is due to both oxidation of the hardening agents such as cobalt or nickel which are typically present in the gold as well as oxidation of underlying base metals diffusing through the gold to its surface. The detailed results for the 125 C aging will not be given, since all systems failed. It may be added that since this work was completed, independent studies have been done at Battelle on at least Lubricants 1 and 6 in which thermal aging conditions on identical samples were 105 C for 500 hours. At these conditions which represent a considerable acceleration over typical use conditions, there was no measurable degradation. This latter information provides a high level of confidence in the conclusions which follow.

The results for the 80 C coupon aging are shown in Figures 42 and 43. These results indicate that Lubricants 5, 7, and 12 showed high and unacceptable levels of degradation. Lubricant 3 showed measurable degradation and what might be considered marginal performance. The remaining lubricants showed generally excellent performance.

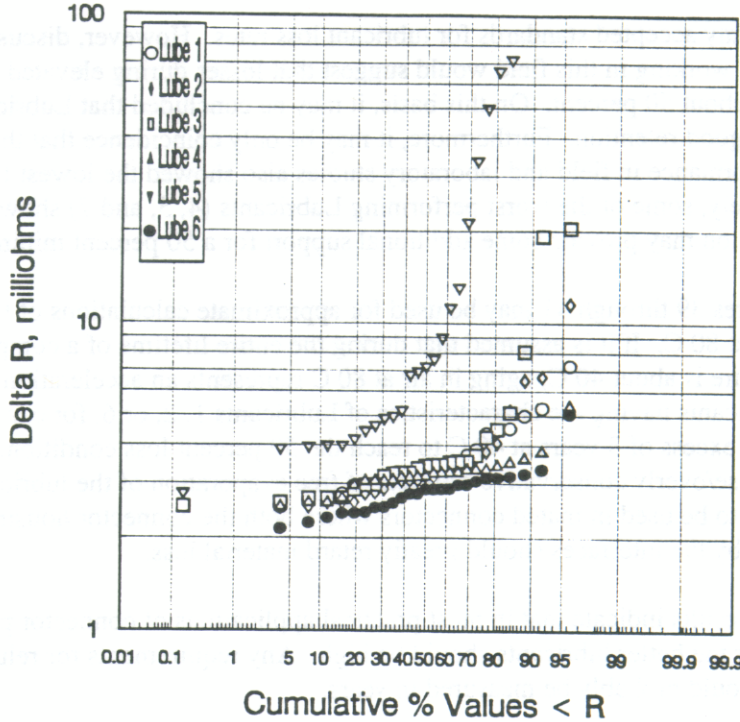

Figure 42. Contact resistance of lubricated gold-gold coupons mated to connectors after thermal ageing; 80 C, 1000 hours

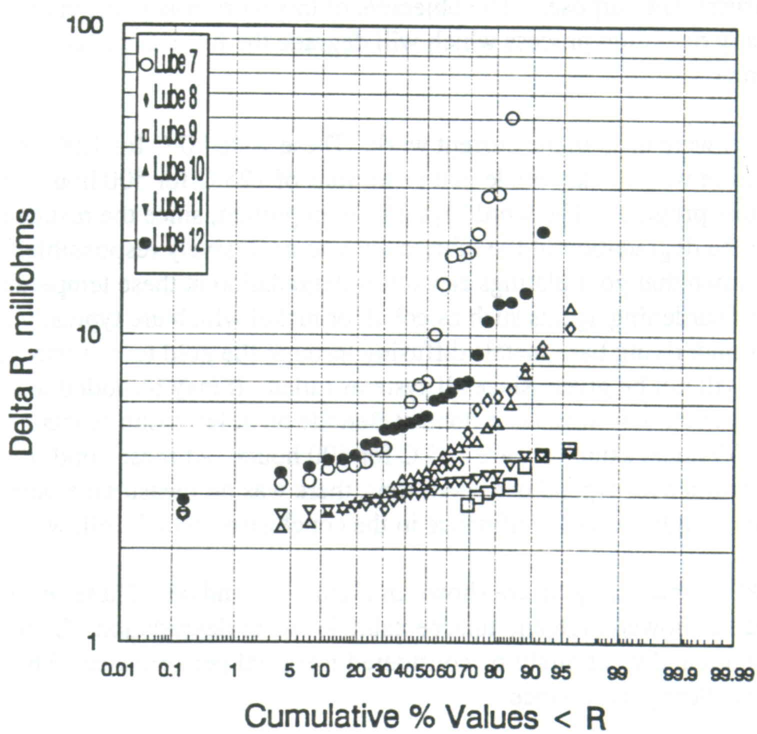

Figure 43. Contact resistance of lubricated gold-gold coupons mated to connectors after thermal ageing; 80 C, 1000 hours

Thermal Aging, Connectors

The final aging experiments in this series were done on lubricated and mated samples identical to those used in the field. The purpose of this work was to determine whether there were any unique mechanisms at a mated interface which over a long period of time could adversely affect performance. For example, at a mated interface, it is known that lubricant will "pool" by capillary attraction. This would provide a natural collection point for any degradation products which, if they developed, could be far higher than those found on the aged coupons as just discussed.

Figures 44 and 45 show the results for these aging experiments done again at 80 C for 1,000 hours. Fortunately, the results are very similar to those presented earlier for the coupon aging.

The conclusion from this work is that thermal aging is important in the qualification of lubricants. These results have led to the conclusion that some of the materials qualified under 81309 will potentially degrade during long-term use and to an extent that connector reliability could be compromised. At the same time, it appears that lubricants are available which provide both excellent long-term stability and a high degree of retention. Among these, Lubricants 1, 2, and 6 appear to offer the best combination of properties.

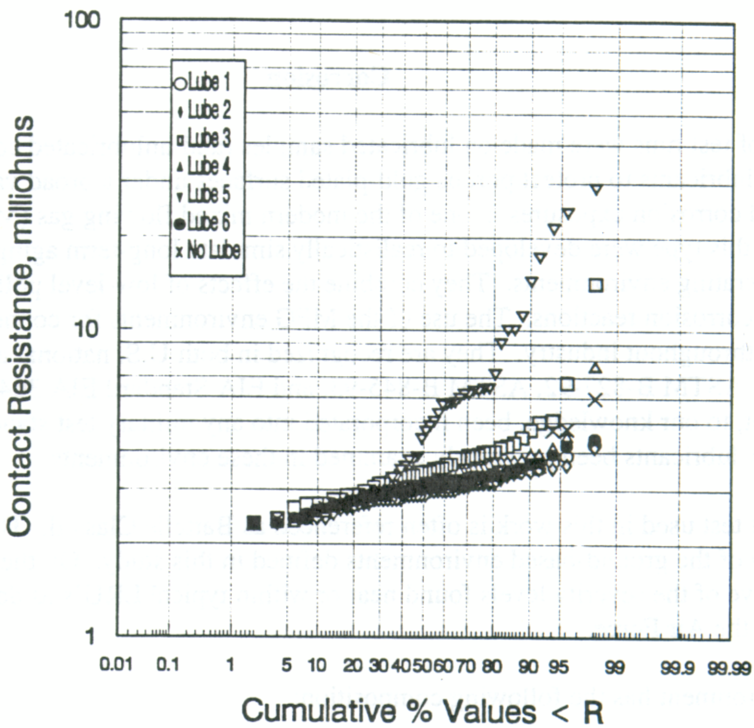

Figure 44. Contact resistance of lubricated connectors after mated thermal ageing at 80 C, 1000 hours in air

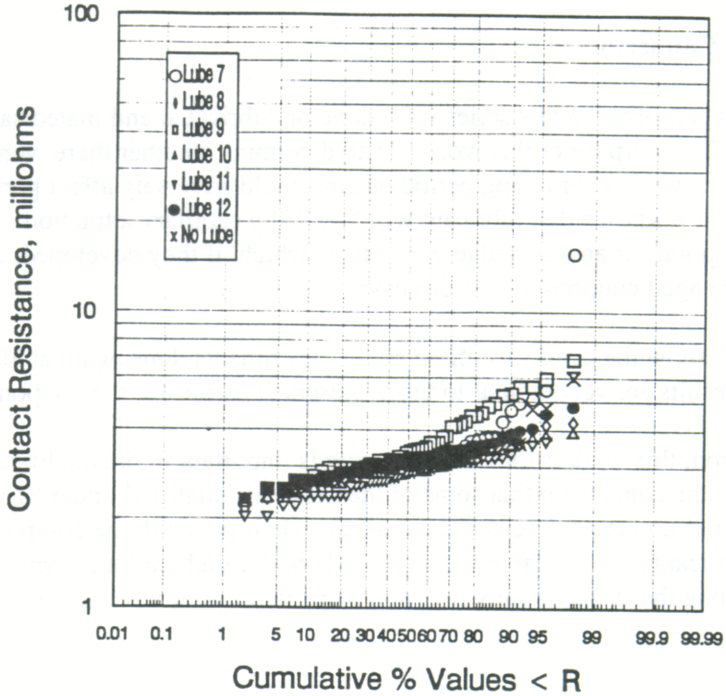

Figure 45. Contact resistance of lubricated connectors after mated thermal ageing at 80 C, 1000 hours in air

Corrosion

A large number of test runs were made on lubricated samples (and unlubricated controls) to confirm the ability of certain lubricants to protect porous gold-plated surfaces under a broad variety of conditions. This work emphasized corrosion exposures in one of the modern mixed flowing gas (MFG) test environments. Environments of this type were developed to realistically simulate long-term aging/corrosion reactions as found in field operating environments. They combine the effects of low-level pollutants and humidity to produce realistic corrosion reactions. The use of the MFG environments for connector qualification is widely practiced throughout industry. They are recognized in both U.S. national and international standards such as ASTM B-827-92, ASTM B-845-93, and EIA Standard EIA 364-B. These standards and practices have not, to our knowledge, been incorporated into any military test standards. Neither have the 81309 or 87177A lubricants been previously examined in these environments.

The level/class of test used in this work is often referenced as Battelle Class II. This severity level is lower than that of many of the ground-based environments defined in this study. On the other hand, it is believed to be representative of the severity levels found near or within typical LRU's as determined in earlier Battelle work for the Air Force.

The Class II environment has the following composition:

10 ppb H_2S
200 ppb NO_2
10 ppb Cl_2
75 percent rh
25 C.

Test chamber configuration and other details were in accord with ASTM B-827-92.

Although this environment was used, the lubricants were put to rather severe tests as a result or preconditioning prior to exposure. First, most of the exposures were conducted on the unmated but lubricated, gold-plated, simulated pc boards. Independent boards were preconditioned in a variety of ways including the following:

1. Lubrication only.
2. Lubricate, extended thermal aging, followed by exposure.
3. Durability/wear cycling prior to exposure.

Unlubricated Gold

Unlubricated gold controls were run in every test series. Figure 46 shows the typical response of one set of controls. While the legend indicates that this particular set was from a thermal aging/preconditioning run, we can indicate that the results for the unlubricated controls under all test conditions were similar.

Two points of reference should be noted from the unlubricated data. First, degradation due to corrosion was rapid. By modern standards, the samples were in a failed state within two days of exposure. From past experience, these are typical results for gold-plated surfaces having defects such as porosity, wear tracks, etc.

A second point which is not specifically shown in Figure 46 is that for unmated exposures on samples without lubrication, it is rare to find any materials in common use surviving for more than 5 days of exposure. The significance of this statement should become apparent in following sections.

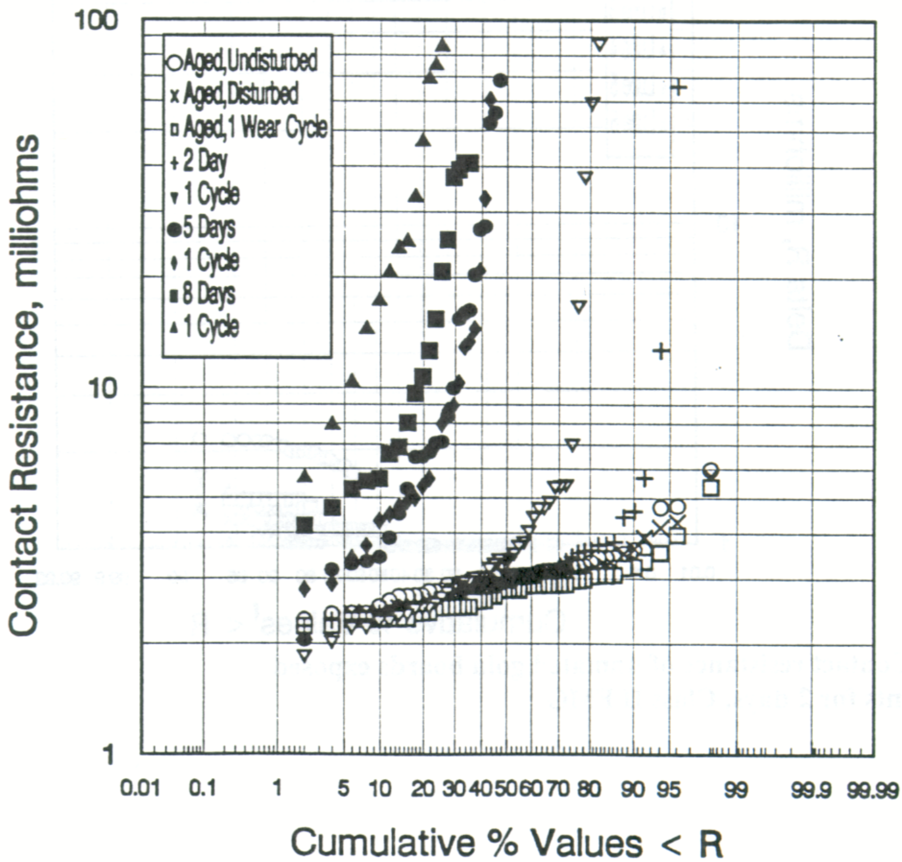

Figure 46. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; no lube

Lubricated Gold

Comparable exposure results on lubricated gold (without thermal aging or durability cycling) are shown in Figures 47 and 48. As a point of reference, a highly desirable objective for the data distributions would be contact resistance changes as low as possible, and particularly, below 10 milliohms.

It is clear from the 2-day data that all lubricants except No. 7 did give improved performance compared to unlubricated gold. The Lubricant 7 samples degraded rapidly and very similar to unlubricated gold as shown in Figure 46. These results are totally consistent with the field results for Lubricant 7. Further results are shown in Figures 49 through 52 for exposures up to 20 days and with and without one mating cycle after initial measurements. The significance of these data may first be found in the statement from earlier investigations that no known materials or lubricants have been shown to survive such extended exposure conditions. While it is unlikely that there would be a requirement for unmated service for this period of time, the results dramatically illustrate the ability of some of these lubricants to inhibit corrosion.

The data in Figures 49 through 52 are in general agreement with field results. Lubricants 4, 5, and 7 gave poor performance. All other lubricants to this point gave a remarkable degree of corrosion inhibition with only Lubricant 8 being considered marginal.

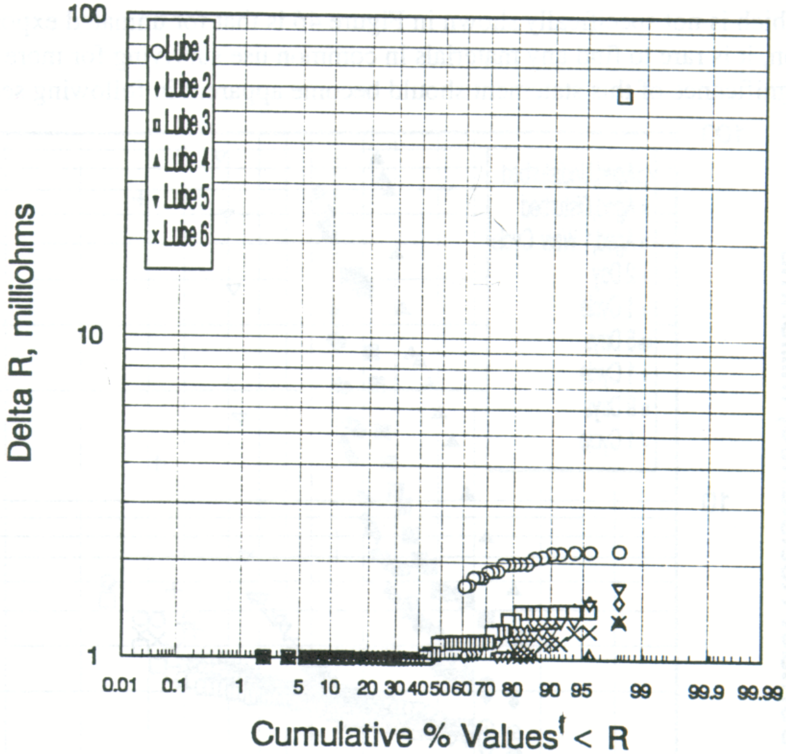

Figure 47. Contact resistance of unmated gold boards exposed with lubricants for 2 days, Class II FMG

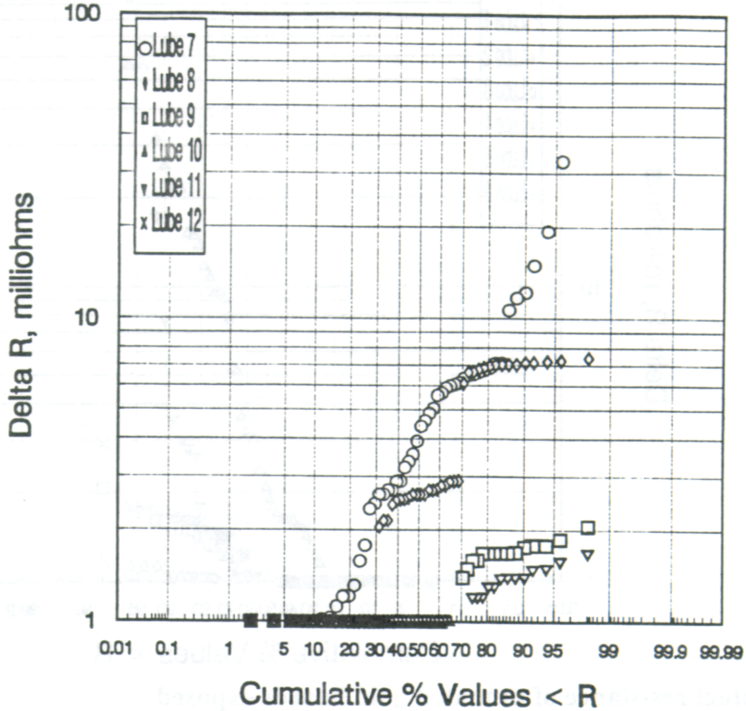

Figure 48. Contact resistance of unmated gold boards exposed with lubricants for 2 days, Class II FMG

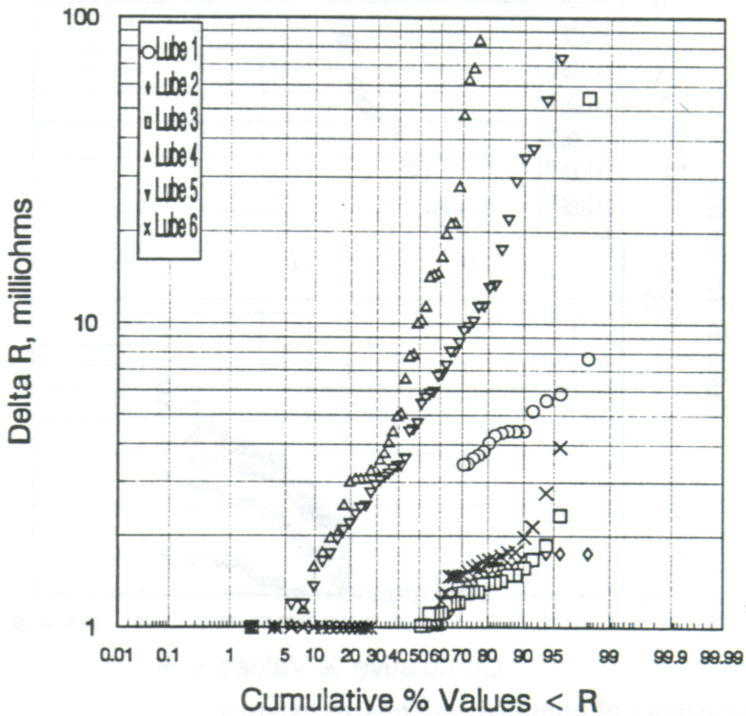

Figure 49. Contact resistance of unmated gold boards exposed with lubricants for 20 days, Class II FMG

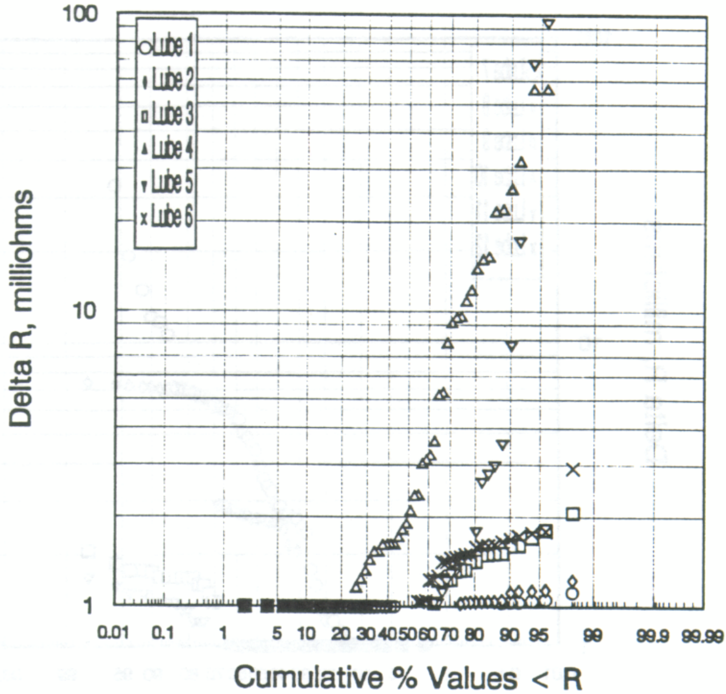

Figure 50. Contact resistance of unmated gold boards exposed with lubricants for 20 days, Class II FMG + 1 cycle

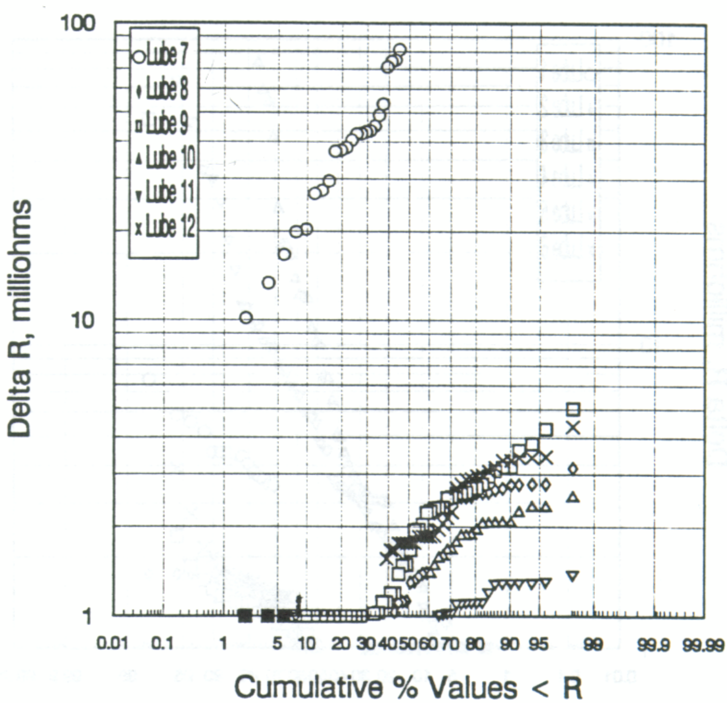

Figure 51. Contact resistance of unmated gold boards exposed with lubricants for 20 days, Class II FMG

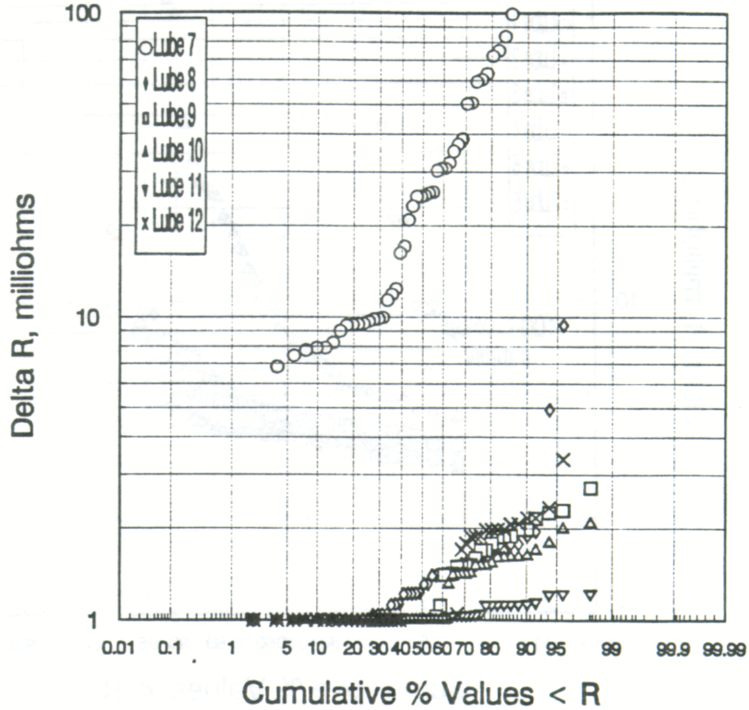

Figure 52. Contact resistance of unmated gold boards exposed with lubricants for 20 days, Class II FMG + 1 cycle

Lubrication and Durability Cycling. It is considered important for any practical application that a corrosion-inhibiting lubricant should remain in place to perform its function during repeated insertion and withdrawal/mating-unmating of connectors. Experiments were, therefore, performed in which samples were lubricated, then mated and unmated 100 times, followed by FMG exposures.

The 20-day results are shown in Figures 53 and 54. It was again found possible to retain corrosion inhibition even under these extreme conditions. Lubricants 4, 5, and 7 continued to perform very poorly while Lubricants 2 and 11 were probably marginal. These results should probably not be considered highly negative for Lubricants 2 and 11 in view of the extreme conditions for these experiments. Nevertheless, lubricants were identified which gave significantly better performance such as Lubricants 1, 6, 9, and 10.

Thermal Aging. Another extreme test was performed in which the gold-plated boards were first lubricated, then thermally aged at 80 C for 1,000 hours, after which they were exposed in the Class II environment.

Detailed data for every lubricant tested in this manner are shown in Figures 55 through 66. These data may be compared to the results shown in Figure 46 for the unlubricated control tested in exactly the same manner.

The results show dramatic differences among the lubricants with respect to their ability to be retained on metallic surfaces and continue to perform a corrosion-inhibiting function. At the same time, some of the lubricants did continue to provide a high degree of protection compared to unlubricated gold. Those lubricants which were considered to exhibit exceptionally good performance under such test conditions were 1, 2, 6, and 11.

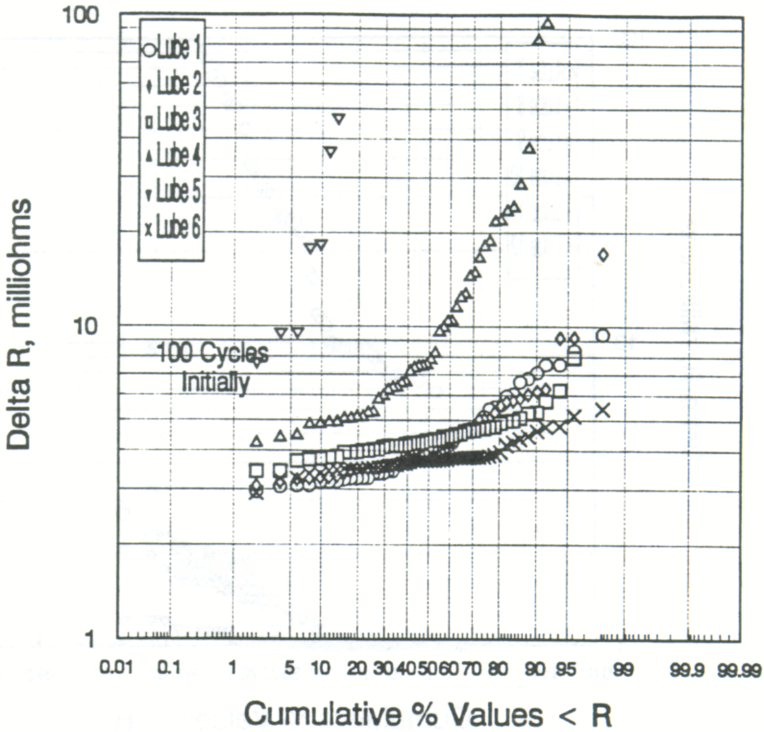

Figure 53. Contact resistance of unmated gold boards exposed with lubricants for 20 days, Class II FMG + 1 cycle

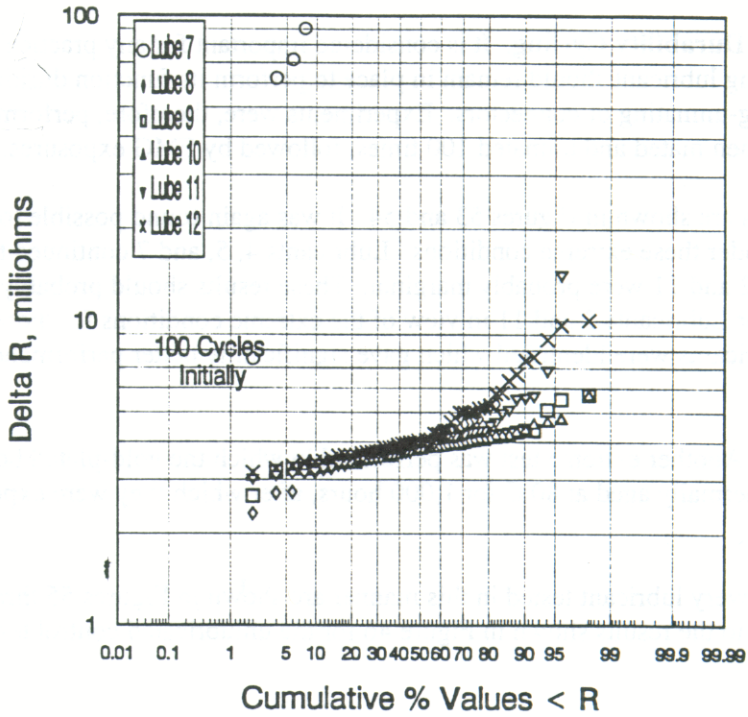

Figure 54. Contact resistance of unmated gold boards exposed with lubricants for 20 days; Class II FMG + 1 cycle

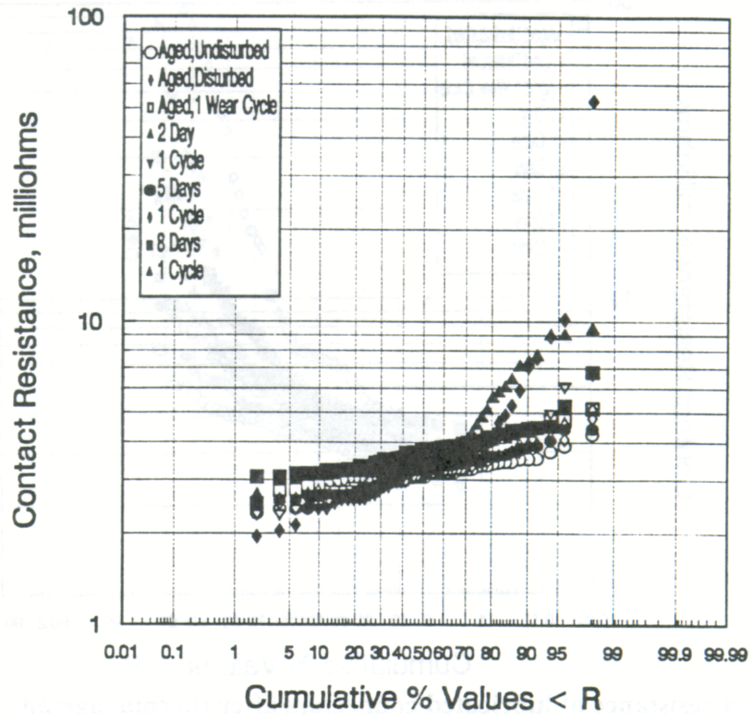

Figure 55. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 1

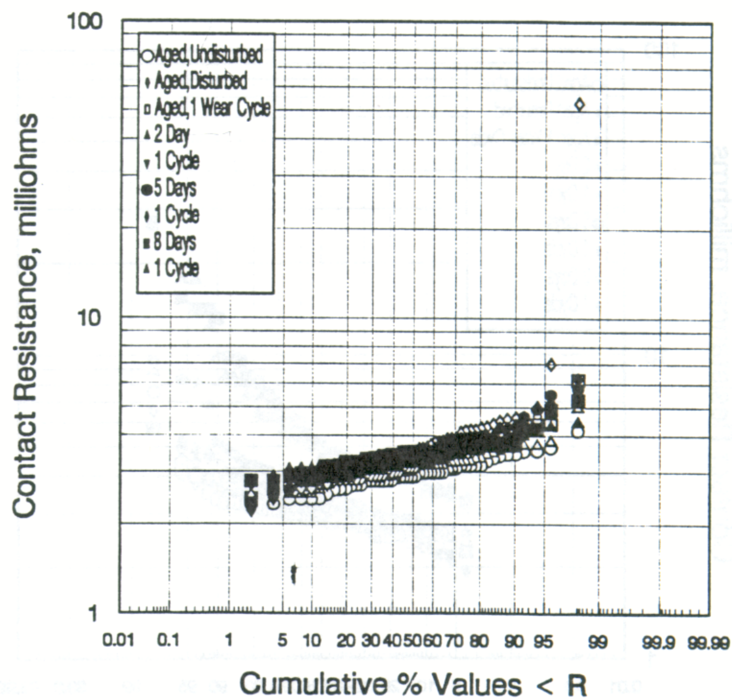

Figure 56. Contact resistance of lubricated connectors after thermal aging at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 2

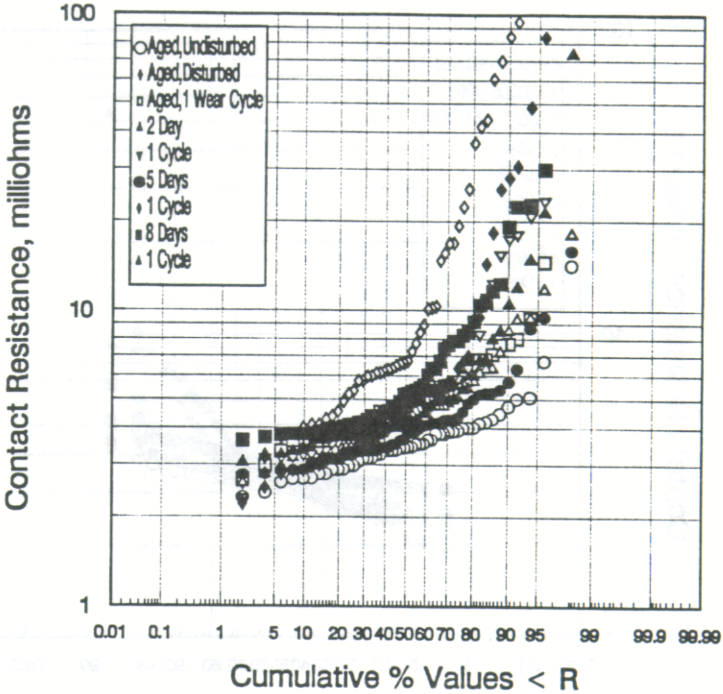

Figure 57. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 3

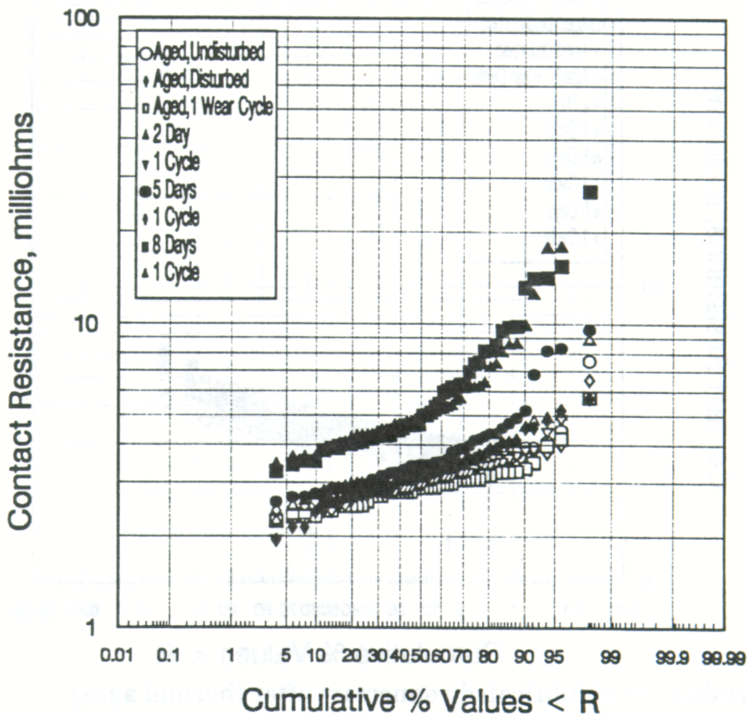

Figure 58. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 4

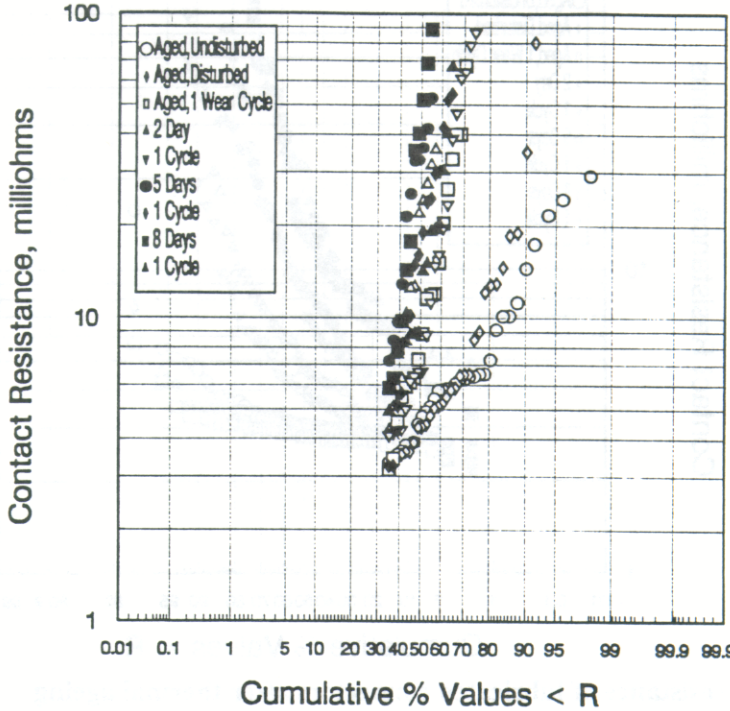

Figure 59. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 5

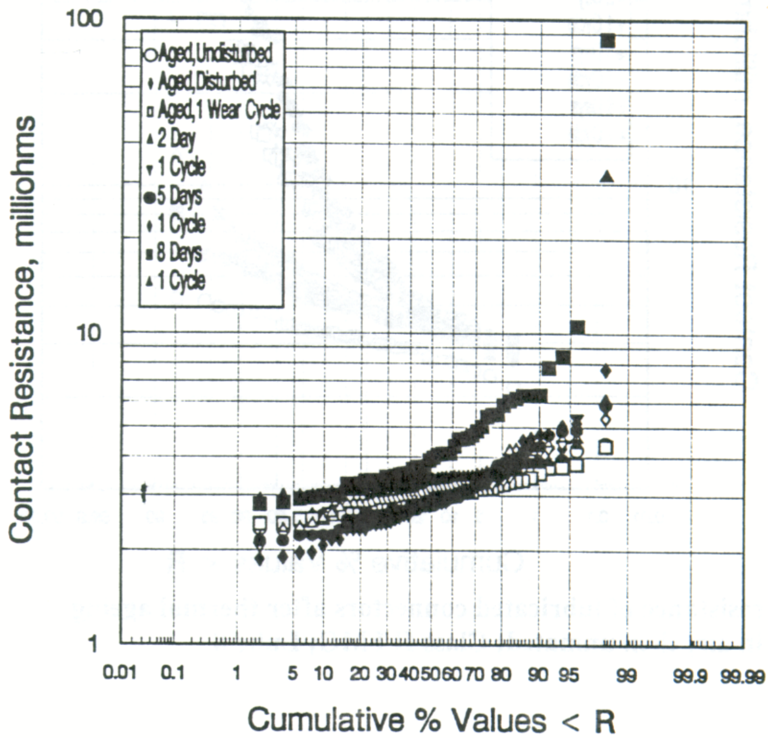

Figure 60. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 6

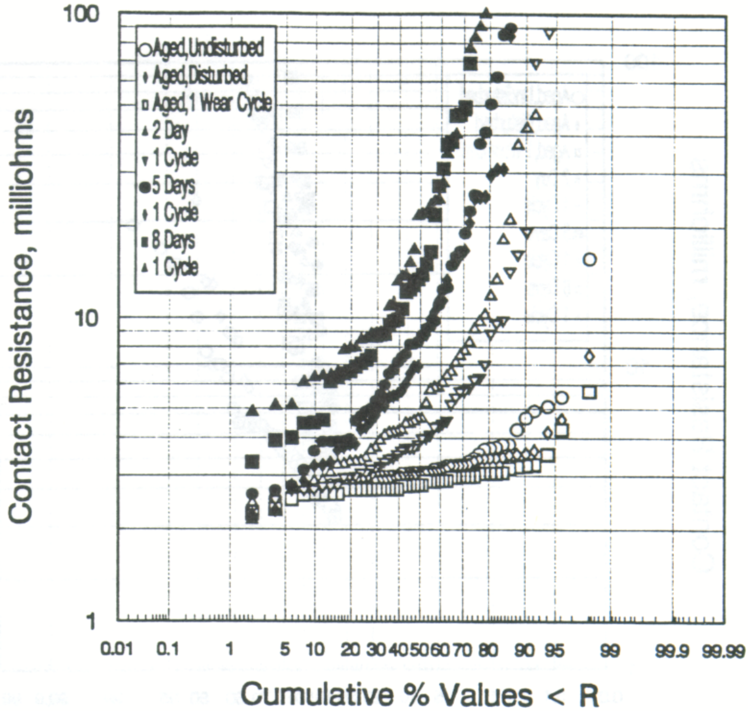

Figure 61. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 7

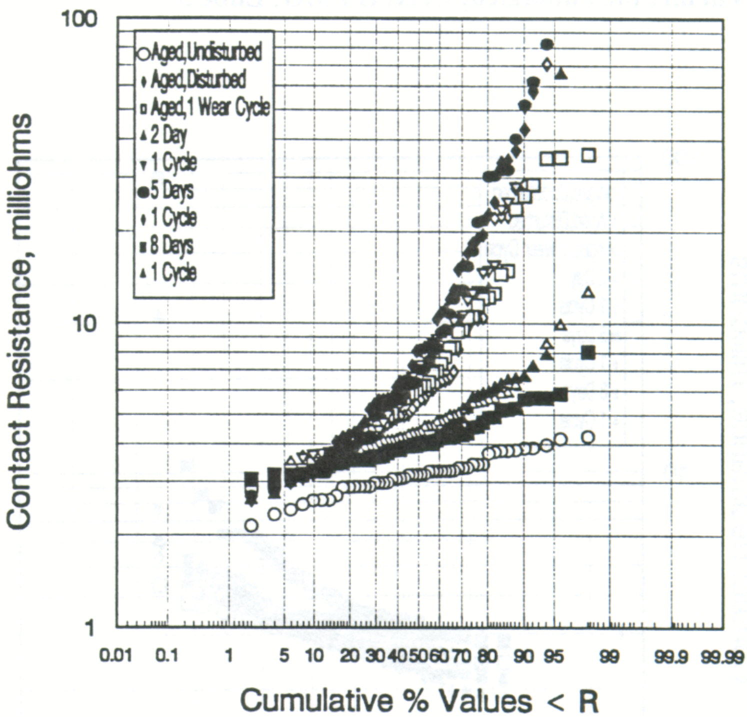

Figure 62. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 8

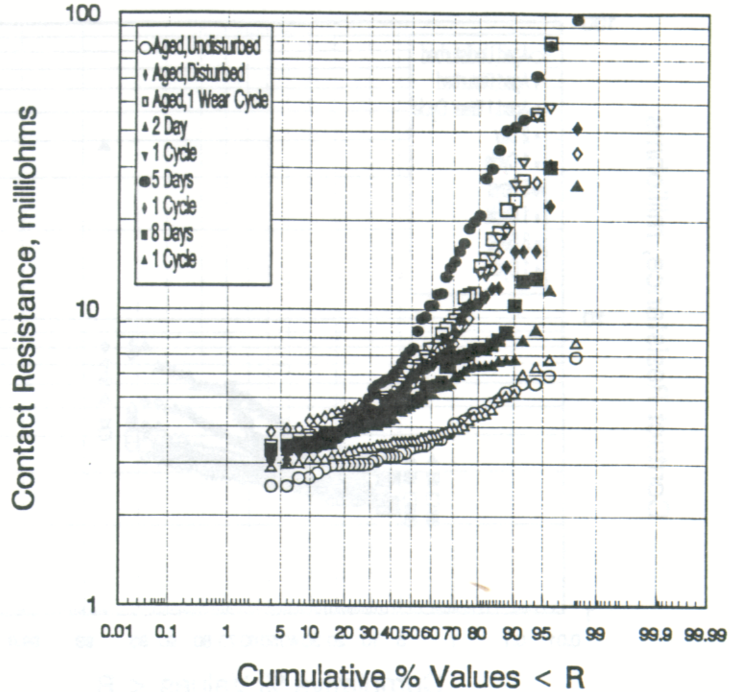

Figure 63. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 9

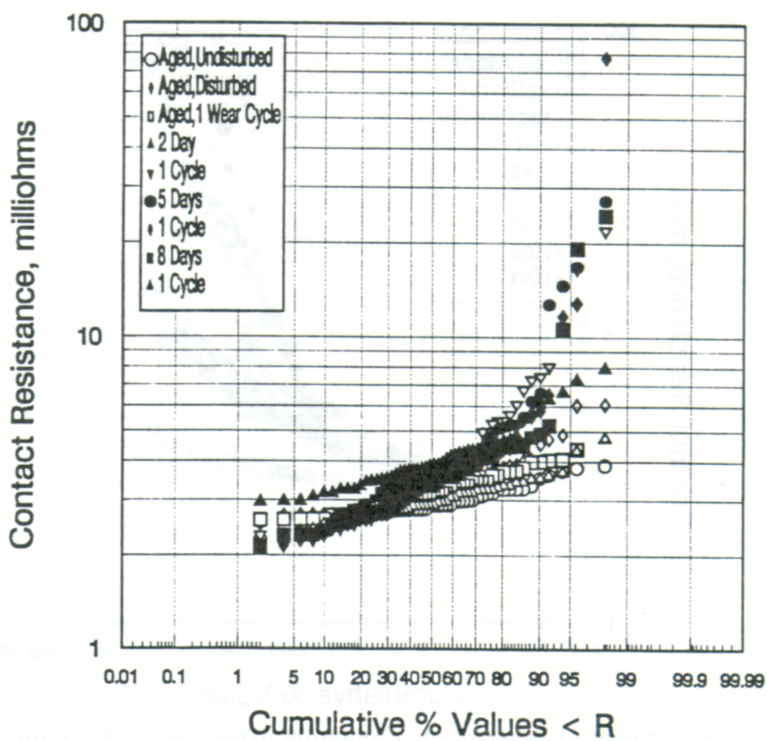

Figure 64. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 10

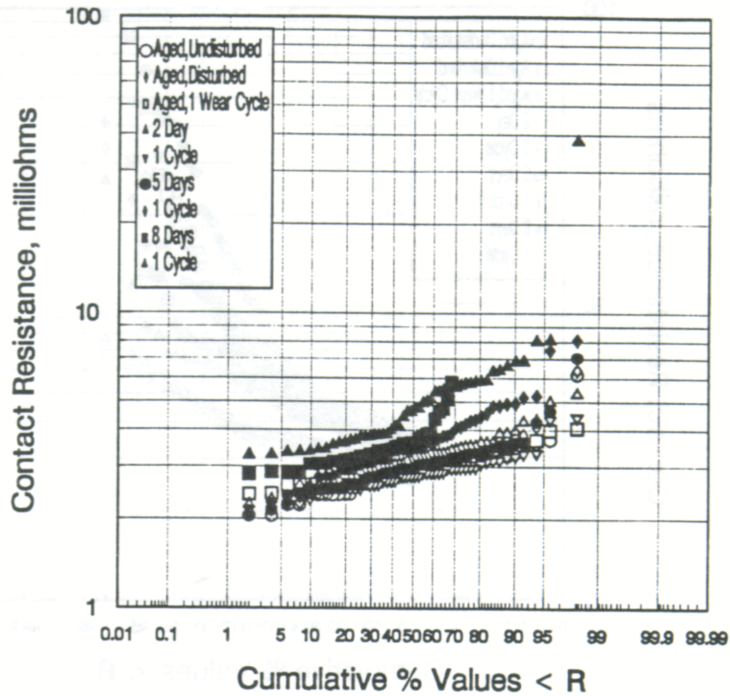

Figure 65. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 11

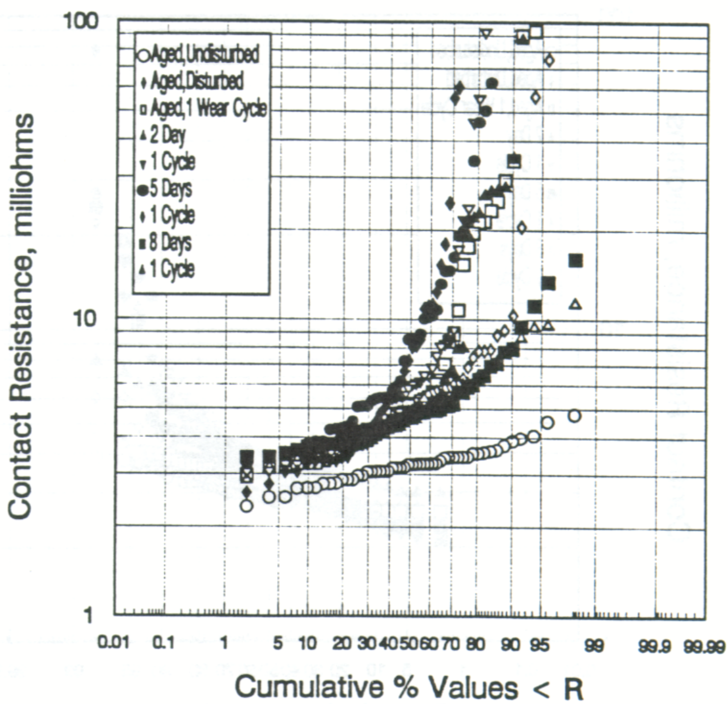

Figure 66. Contact resistance of lubricated connectors after thermal ageing at 80 C, 1000 hours in air; then unmated; Class II FMG; Lube 12

Lubricated Steel Sensors

Laboratory studies were done in which the carbon steel coupons/sensors were lubricated and then exposed in the Class II FMG environment. Visual observations were made as a function of time with the results shown in Table 10.

As expected, steel without any coating corroded/rusted quickly and actually showed 100 percent coverage within less than 1 day. All of the lubricants gave some level of protection, but the results in Table 10 clearly show large differences and results which are generally in agreement with field data as reported in Tables 5 through 8.

In summary, the results confirm that Lubricants, 1, 2, 6, 8, 10, and 11 appear to have a unique ability to inhibit corrosion. These sensor data must, of course, be combined with other results particularly from the connector studies to reduce considerably this list of "best performers".

Table 10. Corrosion of steel sensors in Class II FMG environment

	% Area Corroded After Exposure, days				
Lube	**2**	**4**	**7**	**12**	**20**
0	100	--	--	--	--
1	0	0	0	5	5-10
2	0	0	0	0	5
3	0	<5	5-10	10-15	30-40
4	50-60	80-90	90-95	--	--
5	50-60	80-90	90-95	--	--
6	0	0	0	5	5-10
8	0	0	0	0	5
9	<5	15-20	15-20	20-30	40-50
10	0	0	5	5	5-10
11	0	0	0	0	5-10
12	0	5	5-10	5-10	10-15

Electromigration

There is one remaining but very important aspect of the evaluation of any lubricant for applications such as those anticipated. This involves the dielectric properties of the lubricant. Specifically, the material should be a good dielectric and furthermore, the material should not support the failure mechanism known as electromigration. The latter is simply the development of electrical shorts due to the formation of conducting paths/corrosion products between metallic conductors having a voltage bias between them.

Tests are commonly run to study electromigration using test patterns of the type shown in Figures 67 and 68. This pattern is nothing more than what is known as an interdigitated comb pattern having multiple lines connected onto two bus patterns.

Samples of the type shown in Figure 67 were available from earlier work at Battelle. This type of pattern provided a relatively severe test of electromigration tendency, since these patterns consisted of 4-mil lines and 4-mil spacings. Each pattern had 40 lines or 20 line pairs. In other words, current leakage at any point between any pair would be recorded as a failure.

Samples of the type shown in Figure 67 were wired to circuitry which effectively provided a current limiting resistor in series with each pattern and provided a 50 VDC bias across each path. Samples were individually lubricated, placed in an FMG chamber, and leakage current was continuously monitored.

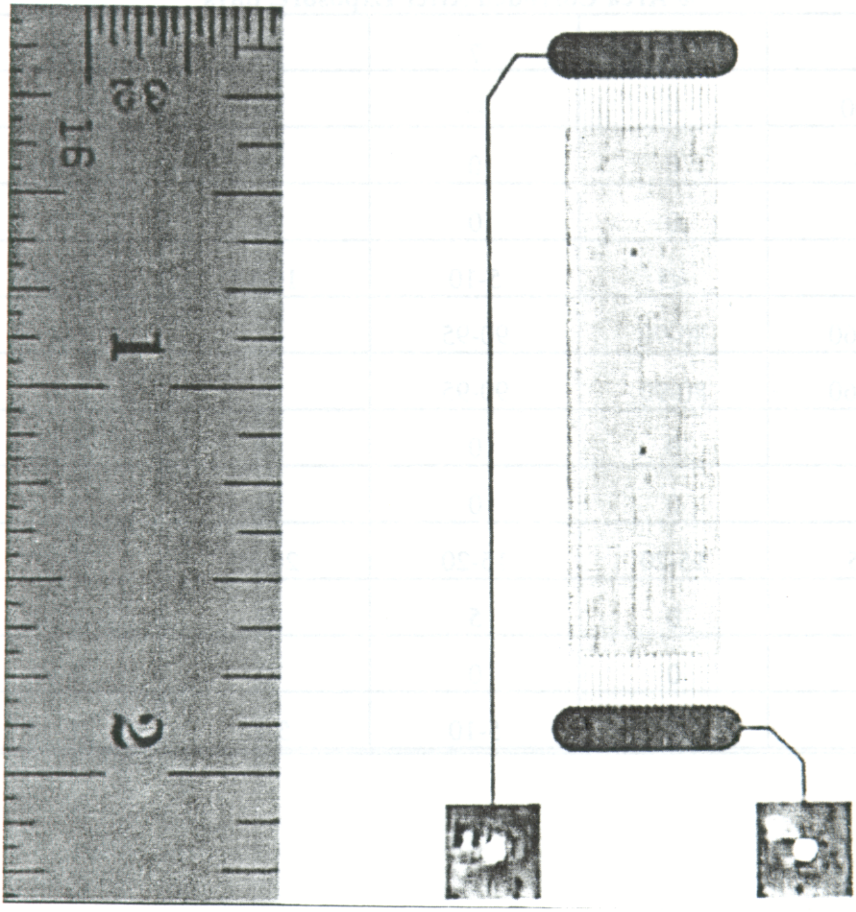

Figure 67. Test pattern for insulation resistance/electromigration studies

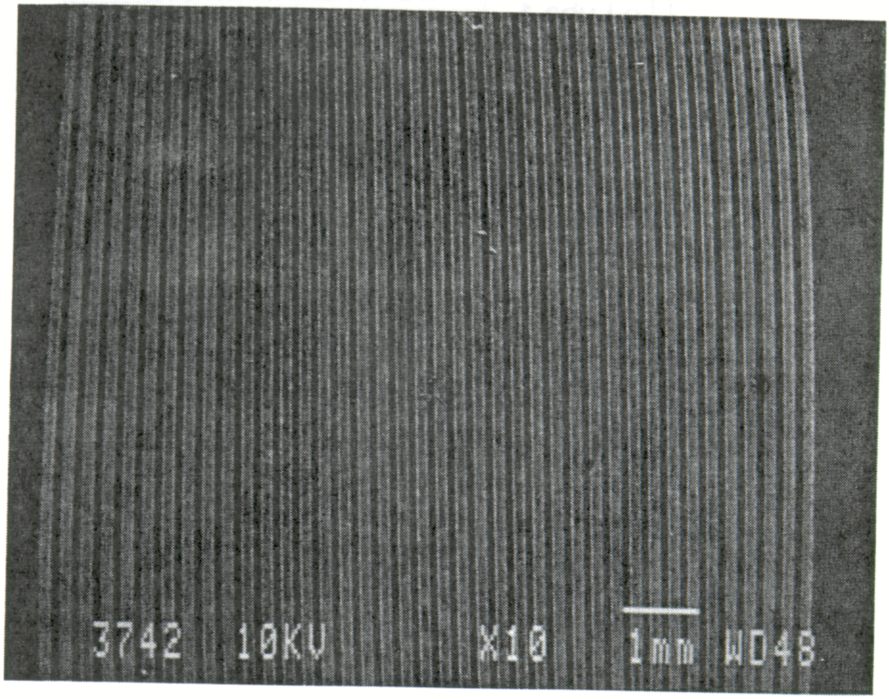

Figure 68. High magnification view of test pattern

Two types of patterns were actually available. One group of patterns had a conventional reflowed solder over copper. The second group of samples consisted of bare copper traces. In neither case was their any solder mask or any other protective coating on the metallic traces other than the lubricant.

On the basis of the positive results reported earlier for the connector hardware in a Class II MFG environment, a decision was made to study electromigration at an even higher level of severity. For this reason, a Class III FMG environment was used which approached a severity level found in many of the outdoor environments from the ground-based study. The Class III environment had the following conditions:

100 ppb H_2S
200 ppb NO_2
20 ppb Cl_2
75 percent rh
25 C.

Results for the solder-coated patterns are shown in Figures 69 and 70. The results should be viewed in comparison to data on the unlubricated controls which typically failed within 70 to 90 hours of exposure. On this basis, several lubricants (4 and 5) were considered to fail more rapidly than the unlubricated samples. The remaining lubricants provided environmental protection, but the results for Lubricant 6 were particularly impressive. Although all other lubricants eventually gave failures, this was the single sample group which did not.

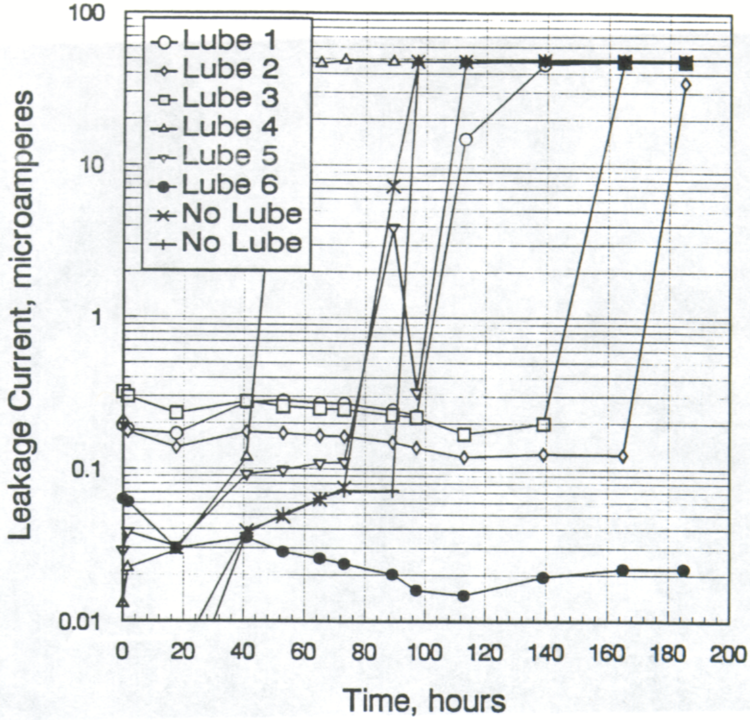

Figure 69. Effects of lubricants on electromigration on fine line solder coated patterns; 4 mil lines, 4 mil spacings; 50 VDC bias in Class III FMG environment

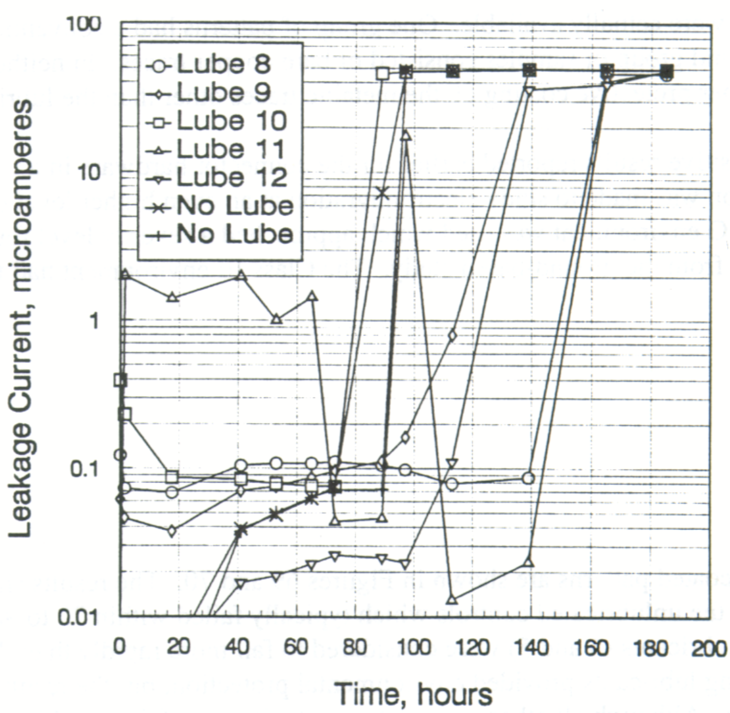

Figure 70. Effects of lubricants on electromigration on fine line solder coated patterns; 4 mil lines, 4 mil spacings; 50 VDC bias in Class III FMG environment

Results for the bare copper patterns are given in Figures 71 and 72. Somewhat similar results were obtained with the unlubricated bare copper traces turning totally black very rapidly and failing within 100 to 150 hours. Lubricants, 3, 4, 5, and 12 actually failed before the untreated copper, but several lubricants showed remarkably stable performance. These included Lubricants 1 and 6 with 2, 10, and 11 showing relatively good performance.

It is interesting to note that the electromigration results for the merits of various lubricants correlate rather well with corrosion inhibition as judged from the connector data and even the steel sensors. While the various failure mechanisms are quite different, the factors determining performance may be very similar in one respect. All of these data may reflect the ability of various lubricants to provide an impermeable film which prevents moisture and/or pollutants from reaching the critical metallic surfaces.

There is one final piece of data in support of this thesis obtained from the studies on the bare copper patterns. The progress of corrosion/tarnish could be followed visually. The bare copper traces, as expected, turned black within 1 to 2 days, although the development of shorts required a somewhat longer period of time.

This observation is in sharp contrast to the observations with Lubricant 6. After about 500 hours of exposure, the copper traces still looked like copper with only the slightest indication that tarnish was just starting. Next, in order of visual appearance, were Sample 2, 8, and 1 which had light tarnish films and which had just become visible at 300 to 350 hours of exposure.

The tarnish films on Samples 10, 11, and 12 were somewhat higher and had become visible in the 200 to 250 hour range.

Samples 3, 4, 5, and 9 were totally discolored/black and it was difficult to distinguish these from the unlubricated copper after 500 hours of exposure. However, visual observations indicated that these samples were not discoloring in the 100-hour range. Again, most of this information directly correlates with the leakage current measurements in Figures 71 and 72. These results suggest yet another interesting sensor possibility for lubricant qualification based on visual observations on copper and/or similar leakage current measurements.

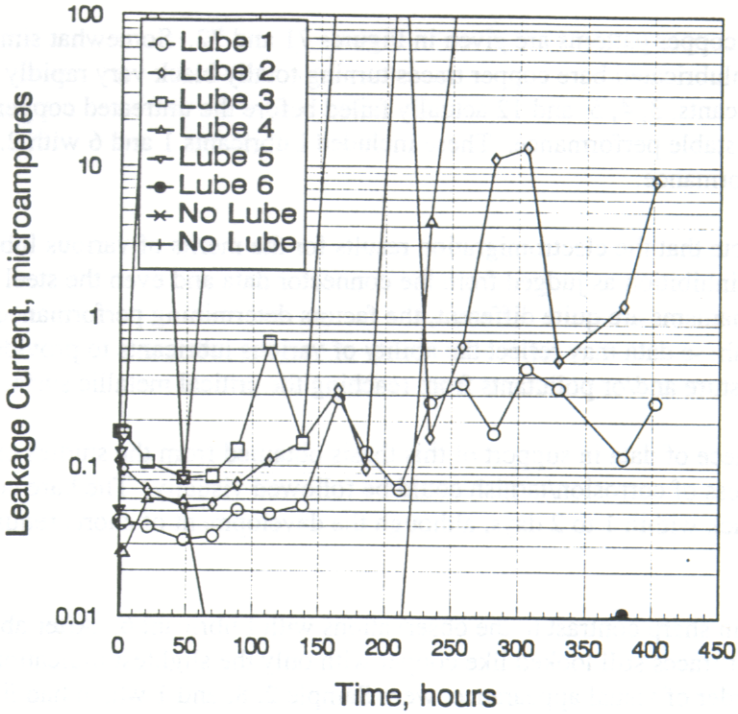

Figure 71. Effects of lubricants on electromigration on fine line bare copper patterns; 4 mil lines, 4 mil spacings; 50 VDC bias in Class III FMG environment

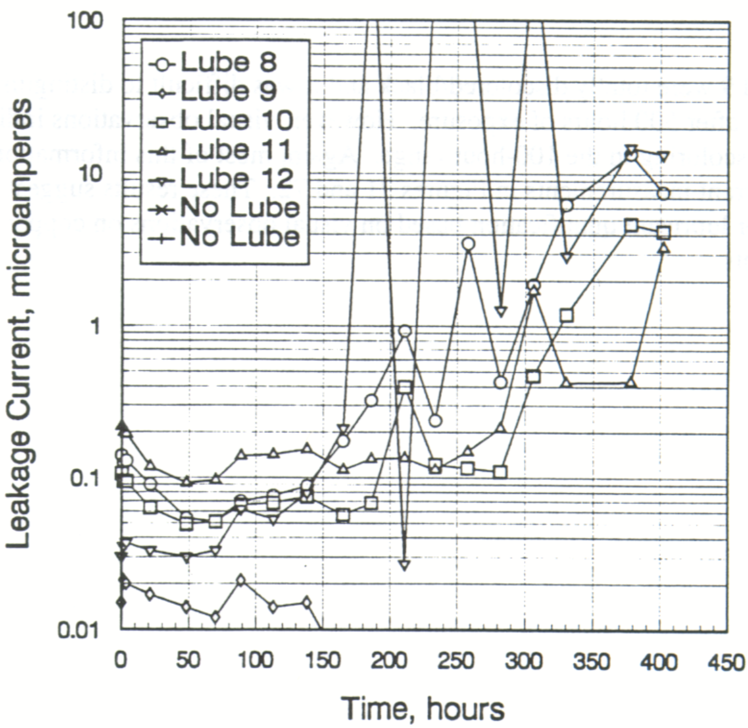

Figure 72. Effects of lubricants on electromigration on fine line bare copper patterns; 4 mil lines, 4 mil spacings; 50 VDC bias in Class III FMG environment

Conclusions

The major and probably most important conclusion from this work has been a demonstration that at least several commercially available lubricants can provide a high degree of corrosion protection to gold-plated electrical connectors. At the same time, it appears that these lubricants would be capable of meeting all reasonable requirements of modern connector qualification procedures and have no known deficiencies/ failure mechanics.

The "best" lubricants identified from this study were those with ID's 1, 2, and 6. All would appear to be adequate and nearly identical in performance although field and laboratory data may slightly favor Lubricants 1 and 6. Therefore, it is these two latter materials which have been recommended for future flight tests.

It should be noted that these particularly conclusions and recommendations are based on data obtained under extreme environmental conditions. Such conditions are not likely to be encountered at the component level of the vast majority of operating electronics including those found in military applications. In these environments of lower severity, these field and laboratory studies demonstrated that most of the lubricants evaluated in this program will provide a clear net benefit.

The latter conclusions are important for users of materials which have been qualified under existing specifications. It is likely that any material which has been qualified under either 81309 or 87177A would meet the primary requirement that use of the lubricant should pose no risk to the system. This conclusion may be reached from the existing data even though the results have shown a large difference in corrosion inhibiting ability among lubricants and that several lubricants may actually promote corrosion in severe environments. Examples of the latter include Lubricants 4 and 5.

The results from this study have demonstrated extremes of lubricant performance. Therefore, the results should present a strong warning against the use of lubricants unless such materials have undergone rigorous qualification. The results obtained for Lubricant 7 have clearly demonstrated the potential effects associated with the use of a lubricant which has not been thoroughly evaluated.

At the present time, the only existing procedure for lubricant qualification is MIL-C-81309E. This standard is believed to be inadequate for the qualification of a connector lubricant, even though its use has led to a unique class of materials whose use would appear to pose little engineering risk. Somewhat similar comments may be made for materials qualified under MIL-L-87177A, even though the specification as written is inadequate for connector qualification.

It is concluded that a need exists for a single standard to be used for the qualification of lubrication in connector applications. This standard should specifically address the problem of corrosion protection of gold-plated electrical connectors. However, on the basis of available technical information and field experience, the same specification may be adequate to address known failure mechanisms associated with the use of other materials including silver and tin.

A recommended specification should incorporate the existing packaging and environmental requirements of 81309 and 87177A. In addition, the minimum technical requirements which are recommended are given in Table 11.

Table 11. Outline of test sequence for connector/lubricant qualification

Test Item 1 -- Edge Card Connector

Gold Plated, 30 microinch minimum gold over 50 microinch minimum nickel; contact normal force 100 gram minimum, 250 gram maximum; minimum sample size = 6 pieces, minimum pin count = 300

Test Item 2 -- Printed Circuit Card

Conventional PC card to fit Item 1 or solid metal simulated PC card; gold plated to specification of Item 1; confirmed porous per ASTM B735-89, ASTM B741-90, or ASTM B799-88; minimum porosity level of 100/cm^2

Test Item 3 -- Lubricant

Candidate lubricant per 81309E or 87177A available in form suitable for spray application to all surfaces of Test Item 2

Test A -- Initial Contact Resistance
ASTM B539-90 or EIA 364 TP 23; all contacts measured before and after lubrication; delta R <5 milliohms for 100% of population

Test B -- Low Temperature
Mated Connectors; Cool samples from + 30 C to -60 C in environmental chamber; measure contact resistance every 10 C ; repeat on heating; delta R <10 milliohms for 100% of population.

Test C -- Thermal Ageing
Mated Connectors; Heat in air at 100 C, 1000 hours; delta R <10 milliohms for 99% of population

Test D -- Durability Cycle
Subject connectors to 100 cycles of insertion and withdrawal; delta R < 10 milliohms for 99% of population for sequence, 98% cumulative

Test E -- Vibration
Mated Connectors; Subject connectors to recognized vibration sequence such as EIA 364 TP28, or MIL-STD-1344A, or Bellcore TA-NWT-001217, Issue 1, 6.1.3.3 procedure; delta R <10 milliohms for 100% of population for sequence, 98% cumulative.

Test F -- Temperature-Humidity
Mated Connectors; subject connectors to standard procedure such as EIA-364 TP31A, Method III; (25-65 C, 10 cycles minimum); delta R < 10 milliohms for 99% of population, 97% cumulative

Test G -- Corrosive Gas
Unmated Connectors; Unmate and subject PC boards to 10 days of MFG exposure per ASTM B827-90 and ASTM B845-93, Method N; delta R < 10 milliohms for 98 % of population for sequence, 95% cumulative

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3) Instrument Society of American Specification ISA SP71.04.

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9) Abbott, W.H.; Connector Corrosion/Fuel Circuit Investigation; Final Report; Contract No. F04606-89-D-0034-QP09 F-16; June 1994.

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11) Generic Requirements for Separable Electrical Connectors used in Telecommunications Hardware; Bellcore, Technical Reference TR-NWT-001217, Issue 1, September 1992, p 58.

Appendix E

W. H. Abbott, "Corrosion Monitoring of Air Force Field Sites
and Effects of Lubrication on Corrosion Inhibition"
(16 pages)

Paper
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CORROSION2000

CORROSION MONITORING OF AIR FORCE FIELD SITES AND EFFECTS OF LUBRICATION ON CORROSION INHIBITION

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ABSTRACT

Work has been in progress for several years to directly measure the corrosive severity of a variety of Air Force bases worldwide. The work has been done for several very diverse reasons. One has been in support of studies to examine the effects of lubricants/CPCs on avionics reliability using the F-16 aircraft as the test vehicle. In this case, corrosion monitoring has been done at ground level to document the external conditions in which the aircraft are based.

A second reason has been to provide a test for current mathematical models which attempt to predict corrosion rates based on available environmental data. A third has been to provide "hard" data on a number of relevant materials and in the process gain additional knowledge about the base environments. The latter refers, in particular, to data relating to total reactive chlorides and/or humidity levels which are recognized to be major "drivers" of corrosion processes. A third reason, has been to develop and validate simple, inexpensive, and reliable methods for obtaining such data. To date more than 50 Air Force sites worldwide have been surveyed.

This paper will review the related results from both studies. It will show the broad statistical distribution of environmental severity levels at active airfields and which differ by a factor of nearly 200:1 . Over this range, the degradation rates of gold plated test connector have been studied and it will be shown that even at the lowest levels of severity reliability can be adversely affected if the external environment is allowed to ingress to the electrical interface.

Studies have also been made on the attributes of commercially available CPCs conforming to MIL-81309E and 87177A. The data will show that a very few of these materials can provide almost total corrosion inhibition at electrical interfaces while posing no know engineering risk. At the same time, some of these same materials appear to be unacceptable/high risk as judged by contemporary standards.

This work has been extended to flight tests on a large population of aircraft. Selected CPCs were applied to avionics I/O connectors on selected LRUs and operational performance was studied over a 2+ year period. Current data show significant improvements in performance as measured by reduced CND rates, lower removals, and reduced maintenance hours. At the same time, the feedback from field personnel regarding implementation was positive.

INTRODUCTION

It has been a longstanding goal of the Air Force to be able to quantitatively describe the corrosion severity of environments in which aircraft are based. It is not difficult to project what the practical value of such data may be, since there has been the assumption that a relationship should exist between environmental severity and corrosive effects on aircraft systems. The nature of such a relationship , if it exists, remains unknown, and this work was initiated with no pre-conceived notion about any necessary relationship.

Corrosion monitoring of outdoor environments is nothing new, and a review of previous work would be beyond the scope of this paper. However, this fact is important to acknowledge, since the type of monitoring to be described in this paper does not represent anything new in principle. Instead what is somewhat unique is the way in which the work was done including sample packaging and data analysis. In fact, it is the first of these items which has been regarded as the single most important variable which has accounted for the good quality of data which was finally obtained.

Some of the more significant efforts in support of the Air Force objectives include the much earlier PACER LIME study (1). This work had as an objective the development of a Severity Classification System for Air Force sites. This was done by attempting to develop algorithms relating the corrosion of metals to a variety of environmental variables, which were known or suspected to be major drivers of corrosion. That work which was done in the early 80's was followed by more recent work which attempted to improve/update the algorithms on the assumption that better corrosion data were available along with more accurate environmental data. (2)

The difficulties associated with these approaches are well known. First and foremost is the nature of available corrosion data and specifically the lack of data obtained in a consistent manner with respect to materials, handling, exposure methods, data analysis, etc: . A second factor involves the very environmental variables, which are the critical inputs to the algorithms. By their nature, environmental variables such as Time of Wetness (TOW), pollutant concentrations, rain, wind, etc: tend to be highly time variant. It is , therefore, difficult to decide how to incorporate these into relatively simple equations. While data for the variables just described are often available from various sources, other variables such as chloride content which are highly critical to the corrosion process are seldom measured. In those cases, values must be inferred. Finally, we must note that strong synergistic effects exist among the critical variables, and for this reason alone the goal of the development of realistic algorithms may be impossible.

Although the latter comments may be viewed as a negative assessment of the prospects of achieving the goal of algorithm development, the situation may not be totally bleak. The work of Reference 2 did lead to new equations and new Environmental Severity Index (ESI) values for all Air Force bases. Many of these predictions have now been tested by experimental data from this work and will be discussed in this paper. However, when these ESI values were published criticisms were raised that in a number of cases the "predicted" severity levels did not agree with intuition or practical experience. In an attempt to resolve these issues and to test the equations, the present experimental work was initiated.

The author had been conducting various field studies for more than 20 years and in the process had developed specific methodologies for obtaining meaningful data in a variety of field environments. Much of this work involved monitoring of indoor operating environments as related to corrosion effects on electronics reliability. The approaches which evolved from this work which have been applied at more than 5000 sites around the world were similar to the methods used in the current studies. The important principal which may be stated involves the following : Directly monitor short term corrosion on relevant metals used as integrated sensors and relate these data to long term effects on components or systems.

Work of this type has been applied in a variety of Air Force programs. However, the origin of this work and its application on a large scale was done in support of our studies on avionics/connector corrosion on the F-16 aircraft and the use of corrosion inhibiting compounds (CPCs) for improved reliability (3). In that work, corrosion monitoring of the base environments was routinely being done to document in a consistent way, the severity of the environments in which specific aircraft were based. That work eventually lead to a more general effort for the use of the same techniques to obtain CSI values at a relatively large number of Air Force sites.

This work is continuing, but a large body of data has already been obtained to begin to describe the statistical distribution of CSI values among Air Force sites worldwide. This paper will review the current data and begin to relate these values to actual effects.

EXPERIMENTAL APPROACH

Corrosion Monitoring

The work being described does not represent anything new in principle. It involves the use of a matrix of specially prepared metallic coupons, which are placed in the location to be monitored. These coupons act as integrated sensors, which corrode under the influence of all relevant environmental variables. Corrosion is measured in most cases as a weight loss value (weight gain data are also routinely recorded). In this regard, the work may be regarded as "conventional".

The unconventional nature of the work is perhaps the key to the being able to obtain consistent and high quality data. This involves the preparation and packaging of samples and the entire handling process from preparation, to deployment, to retrieval.

The details of the corrosion monitoring have been presented elsewhere (3,4) and will not be reviewed in detail in this paper. Examples of the test packages which were deployed at many test sites are shown in Figures 1 and 2. The important features involved in this work included 1) the metallic coupons and the specific intelligence that could be obtained from each, 2) the ability to utilize the mails and on-site personnel to manage samples while obtaining, 3) high data quality, and with 4) relatively low cost.

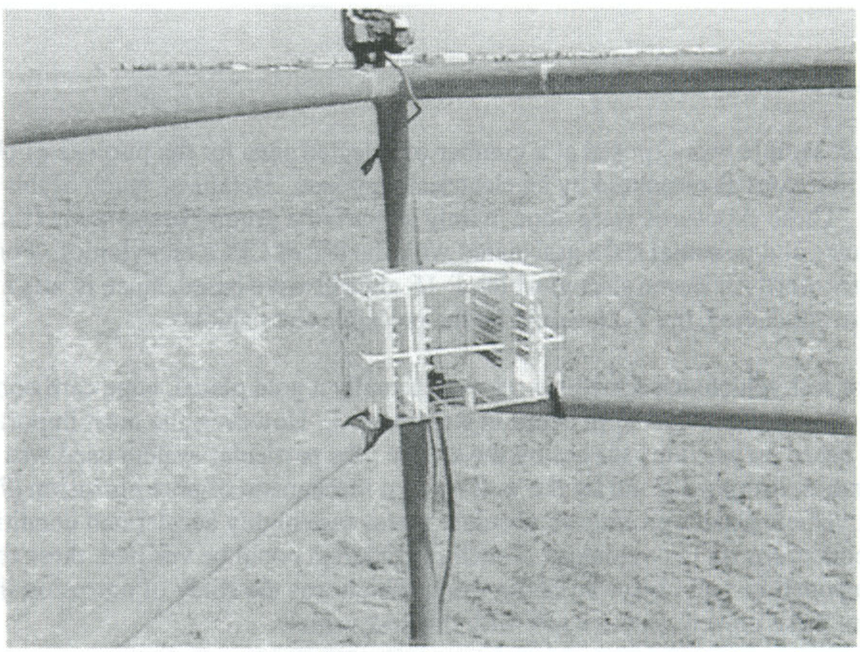

Figure 1. Typical Corrosion Test Package and Mounting

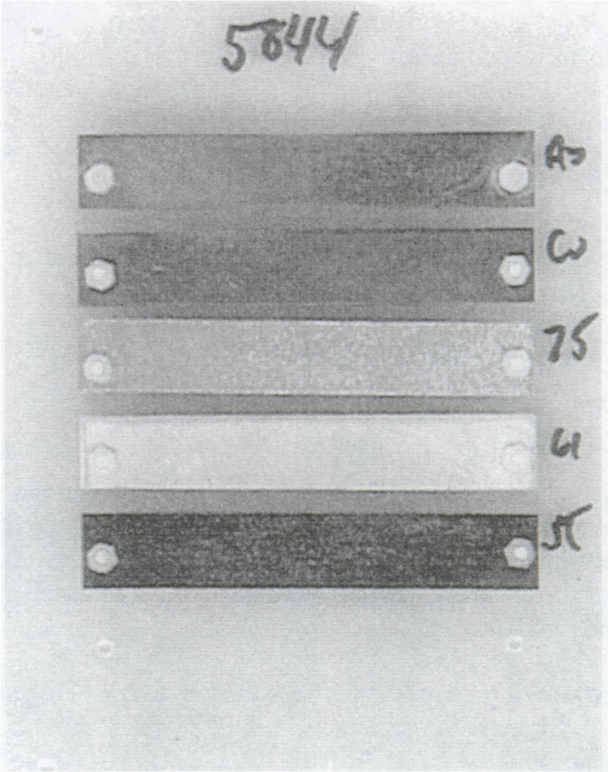

Figure 2. Example of Corrosion Test Card with 5 Metallic Coupons

The metallic coupons involved in this work have routinely included silver, copper, aluminum (6061 and 7075), and carbon steel (1010). Data were obtained at each site over 1 year with quarterly sample retrievals. Samples were analyzed using conventional weight gain/weight loss methods with post exposure cleaning per ASTM G-1.

Connector Test Hardware

A standard test sample was exposed at a number of selected sites for the purpose of obtaining a large body of data on degradation rates as measured by an electrical response. Details of much of this work can be found elsewhere (3,5,6). These exposures were done mainly as part of a ground based study (field and laboratory) to examine the performance and potential risks associated with the use of CPCs on avionics. For this reason, many of the exposure sites were Air Force sites at which F-16 aircraft were based, since is was anticipated that if a flight test program were conducted, the F-16 would be the probable test vehicle.

The connector test vehicle used in this work was actually a gold plated, edge card connector. The reasons for its selection have been reviewed in detail in Reference 3. However, the most important reasons for its use include the fact that based on previous studies by the author , the particular system used was known to degrade rapidly in adverse environments and by the well-known mechanism of pore corrosion (7). Therefore, it was argued that this test vehicle should provide an absolute worst case/highly accelerated condition for corrosion compared to expected conditions on the avionics. If such degradation could be verified, these data would provide a basis for comparison against the real objective of the work, which was the study of corrosion inhibition by CPCs. As will be shown, these objectives were met with this test vehicle.

The identical connector test vehicle was used in an extensive laboratory evaluation of the performance of the various CPCs. In fact it was this study supported by the field studies, which eventually lead to the selection of 2 commercially available materials for flight tests.

Lubricants/CPCs. The terms lubricants and CPCs will be used interchangeably in this paper. A number of Commercial Off The Shelf (COTS) materials are available which conform to the two Military Specifications which applied to this study. These are MIL-C-81309E and MIL-C-87177A. With one exception all of the CPCs studied in the ground based phase of the work were selected from these two groups. A total of 12 such materials were evaluated and it is believed that this covered virtually all of the materials, which were commercially available at that time.

In this paper, reference will be made to CPCs only by numerical designations. This will follow the same shorthand designation found in Reference 3.

In the ground-based studies, the CPCs were applied by spraying onto the test samples under controlled laboratory conditions. In the subsequent flight tests, selected CPCs were applied on the flight line or AIS shops by military personnel. Minimum instructions were provided other than reference to the procedures of T.O. 1-1-689.

Field Sites. With few exceptions the field sites used in this work were active Air Force or ANG bases. Attempts were made to obtain broad geographic coverage and a wide range of perceived levels of environmental severity. To date about 50 sites have been sampled through 9-12 months of exposure.

EXPERIMENTAL RESULTS

Data Distributions

Kinetic data have been obtained at all sites on a quarterly basis over a 1 year period. These results have been presented elsewhere (4) . A key feature of the kinetic data has been the fact that all results have tracked a consistent trend with no unusual data points. This has been interpreted as a strong indication of the success of the entire procedure including sample preparation, packaging, transport, and handling.

The corrosion rate data have been analyzed for all sites to show the range and distribution of data across these sites. The results for aluminum are shown in Figure 3. Similar results and conclusions have been found for steel and copper sensors (4) and for the purposes of this paper, the present data should suffice. These data begin to show the range of conditions potentially faced by aircraft based at various locations.

It should be noted that included in these data are results for a few sites, which are not Air Force locations. They were studied for other reasons and since the data were available they have been contributed to the database. These include the sites listed as DAB (company owned coastal site at Daytona Beach, Fl.), Daytona airport, Abaco Island (remote site in the Bahamas); Athens (Greece; airport).

All of these data show a very wide range of conditions as measured by net corrosion or chloride exposure. This range is approximately 160:1 for aluminum and similar for the other metals.

While these data may be of interest for scientific reasons, it may be difficult for the casual reader to relate to the magnitude of these numbers. As indicated earlier, data such as these gain added significance if and when they can be related to actual effects on aircraft systems. While such work is beyond the scope of this paper, this will be addressed in a small way in the final section of this paper. However, for the moment a few comments can be added to attempt to place these numbers in perspective.

For example, the question might be asked relative to Figure 3, what level of severity would be required in order for bare 6061 aluminum **not** to show visible corrosion within 1 year. To our knowledge, this condition was met at only one site . This was GT. Falls, MT. And a severity condition at the very bottom of the site distribution. This question might be expanded to ask at what level the same type of material would appear to show moderate visual degradation within 1 year. Again, this condition was met at a relatively low level of severity in the range of Fresno and Nellis.

In summary, the conclusion from this work is that for a very high percentage of current Air Force sites, bare aluminum will show significant, pitting corrosion within 1 year.

Effects Of Corrosion On Components

As indicated earlier, a standard gold plated connector test package was installed at a subset of the locations for which corrosion monitoring data are shown in Figure 3. These locations actually covered the entire range of severity levels. This section will discuss the degradation rates found on samples with no CPC treatment.

No-Lube Connectors. Figure 4 shows a large body of contact resistance data, which represents a composite of all results for all sites. Samples were measured on a quarterly basis , and as a result data are available to show the rates of degradation on samples of this type.

The form of the data as a statistical distribution of all measurements is a very common type of presentation used by workers in this field. A full discussion of the interpretation of the distributions is beyond the scope of this paper. However, an important concept is that the high resistance "tails" of the distributions represent a direct indication of degradation and risk. To illustrate this point, a curve has been added to Figure 4 to show what would approach an ideal or low risk distribution for field or laboratory data. In simple terms, a goal would be to find a relatively flat curve, with very small changes in resistance, and no "tail" on the distribution.

With this background, the interpretation of Figure 4 should be obvious. Samples of this type degraded quickly and severely in those environments where the severity was sufficiently high to cause corrosive degradation by a pore corrosion mechanism.

The latter point is important, since Figure 4 does **not** immediately indicate that all samples at all locations were degraded. It simply indicates that as a sample population distributed across a large number of field sites, a high percentage of samples degraded rapidly.

The correlation of degradation with severity levels is addressed in Figures 5 and 6. Data for 2 locations are shown and their approximate severity levels can be referenced to Figure 3 . Figure 5 shows results which should intuitively be correct, but which has never been quantified in this manner from field data. The important conclusion from Figure 5 is that even at the low level of severity of Base B, the degradation was sufficient that within 1 year the sample population was degraded to an extent that would be considered high risk if that level of degradation were found on similar components in modern electronic systems.

These points are further amplified in Figure 6 in which a correlation has been attempted between two very diverse data sets. These are 1) the corrosion monitoring data from metallic sensors per Figure 3, and 2) electrical degradation as measured by a particular statistic (70th percentile) of the resistance distribution as found for each location where connector test samples were installed. Two important conclusions emerge from this work. One is that a strong correlation is shown. This indicates the potential for using simple corrosion monitoring data for predictive means of effects on actual system. The second conclusion is that significant effects/degradation extend to very low levels of severity.

The latter conclusion actually provides an introduction to the next section, since there is an obvious conclusion from this work. This is that sensitive components including gold plated connectors must be protected against ingress of the environment to the electrical interface. If this cannot be assured by adequate sealing or other means of environmental control, then some others means of protection should be employed. The data again stress that point that this is true for operations across virtually all levels of environmental severity.

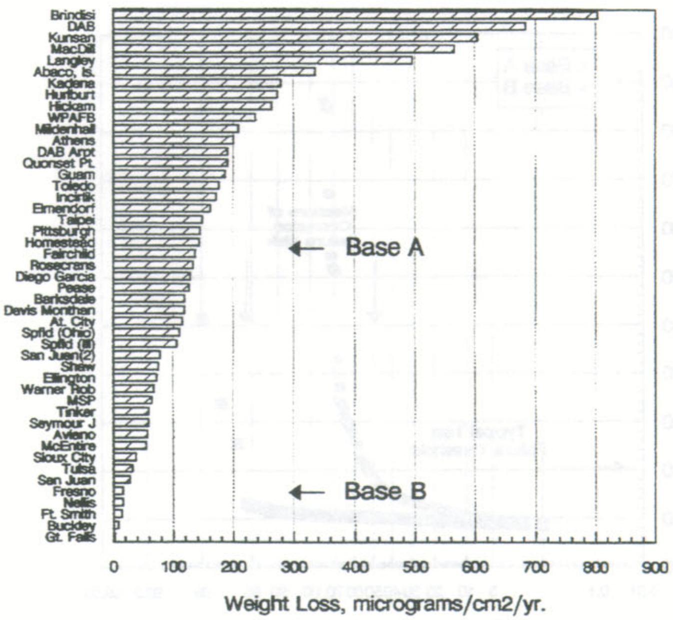

Figure 3. Weight Loss on 6061 Aluminum at Outdoor Field Sites; 270-365 Day Exposures Normalized to 1 Year

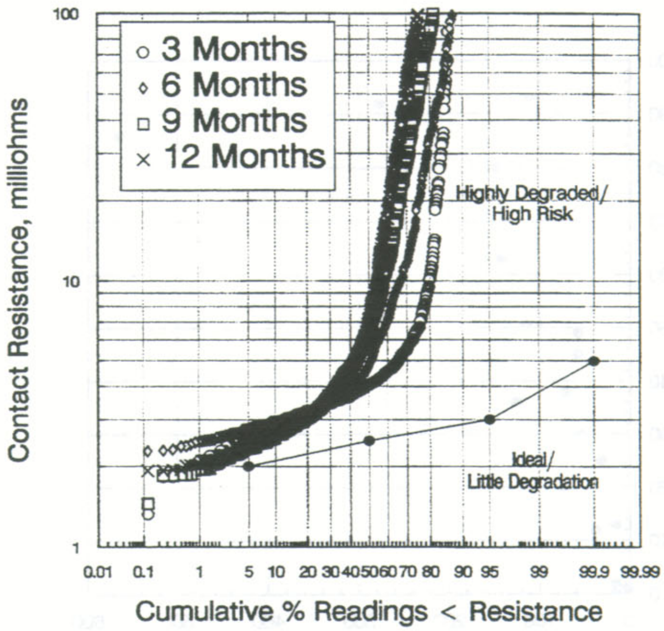

Figure 4. Contact Resistance of Mated Gold Plated Connectors Exposed at 12 Air Bases; Outdoors; No Lubricant

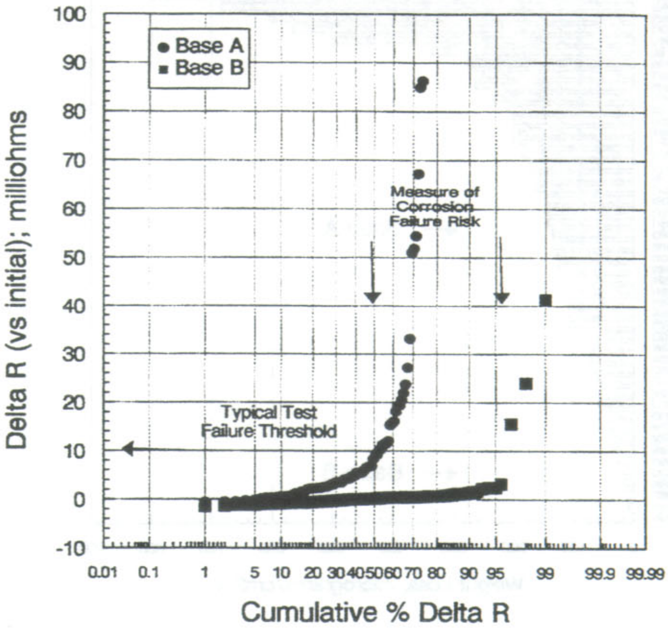

Figure 5. Contact Resistance Change of Gold Plated Connector Test Samples Without Lubricants; Two Bases; 1 Year Exposed

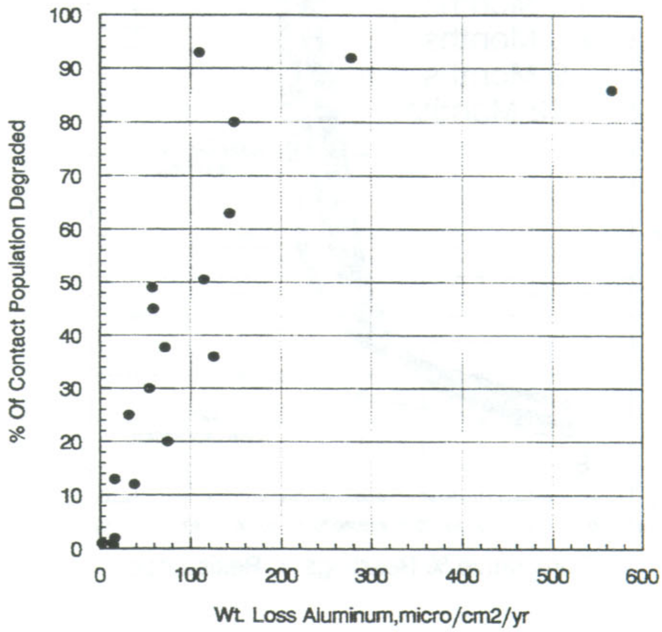

Figure 6. Gold Plated Test Connector Reliability Versus Aluminum Corrosion Rates by Base; CY 1998 Data

Lubricated Connectors – Laboratory Qualification. Prior to the flight tests which are discussed in the final section of this paper an extensive laboratory and ground based program was conducted to evaluate the attributes of the various CPCs qualified under the applicable MIL specs. The reason for this was our position that both the testing requirements and any data which were immediately available were totally inadequate to evaluate the risk associated with the use of these materials for the intended applications. The stated position was that at a minimum and before any flight tests would be conducted, it was necessary to demonstrate the following:

1) No known engineering risks to systems or personnel
2) Under a worst case situation, the system should not be in a condition any worse than if the CPCs had not been applied.

In simple terms, it became necessary to demonstrate that for all reasonable or expected extremes, the CPCs could not cause any harm to systems and at the same time might provide enough benefit to justify their use.

A comprehensive laboratory evaluation was conducted on what appeared to be the 12 candidate COTS materials at that time. A full discussion of all results can be found in Reference 3, but the data in Figures 7 and 8 should illustrate a major conclusion from this work.

These data show the effects of moderate, long duration thermal ageing on the stability of the CPC materials. Thermal ageing is a standard type of stress designed to evaluate possible decomposition of a material to harmful compounds. This is probably the most important in a risk evaluation. However, thermal ageing is also important to evaluate whether the material will be lost (evaporation, migration, etc) over time in which case it may not be available to perform its intended function.

Figures 7 and 8 show very large and often unacceptable differences among these materials even under what is considered moderate and commonly used thermal ageing conditions. At the same time some of the materials proved to be very stable. These data alone were sufficient to exclude certain CPCs from further consideration.

The following conclusions should be stressed:

1) The CPCs qualified per the referenced MIL Specs differ greatly in all aspects of their response on electrical interfaces
2) Some CPCs appear to be high risk and are not recommended for flight
3) The present specifications are totally inadequate with respect to qualification.

The data in Figures 7 and 8 along with other data to be presented should present the following strong warning. This is that materials of this type should never be used in an arbitrary manner and without adequate supporting data to demonstrate their suitability for the intended applications.

Lubricated Connectors – Ground Corrosion Studies. Large numbers of lubricated test samples were installed at various locations across the distribution of Figure 3. Figure 9 and 10 show results for one of the most extreme conditions of severity and which illustrate the major conclusions from this work regarding corrosion inhibition.

Data are shown for all CPCs. Also, to place these data in perspective, similar data are shown for the untreated condition. The conclusions are immediately obvious.

1) A few lubricants provided almost total corrosion inhibition even for this extreme condition
2) A larger number of lubricants provided marginal to little benefit
3) A few lubricants appeared to cause degradation worse than for the unlubricated condition !

These conclusions are not isolated events. They are in direct agreement with laboratory studies and results obtained from other bases. They again stress the conclusion that these materials should not be selected in an arbitrary manner and should only be used based on the availability of sound qualification for electronics applications.

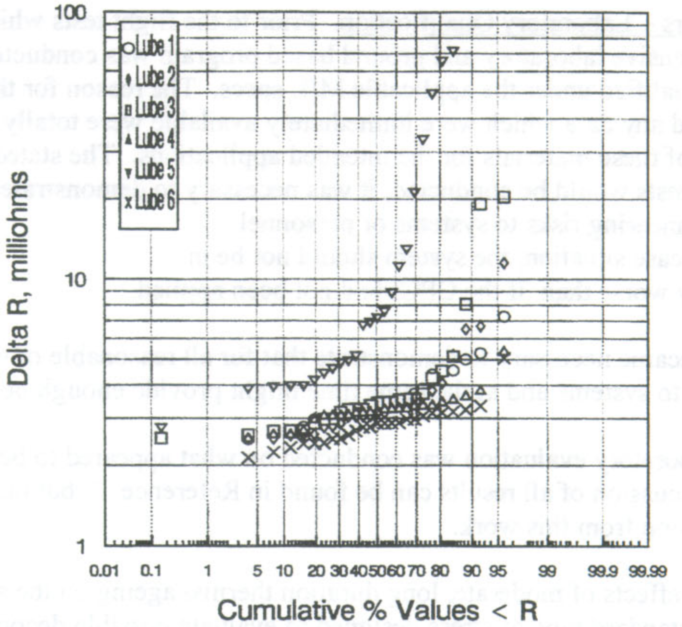

Figure 7. Contact Resistance of Lubricated Gold-Gold Connectors After Thermal Ageing; 80 C, 1000 Hrs

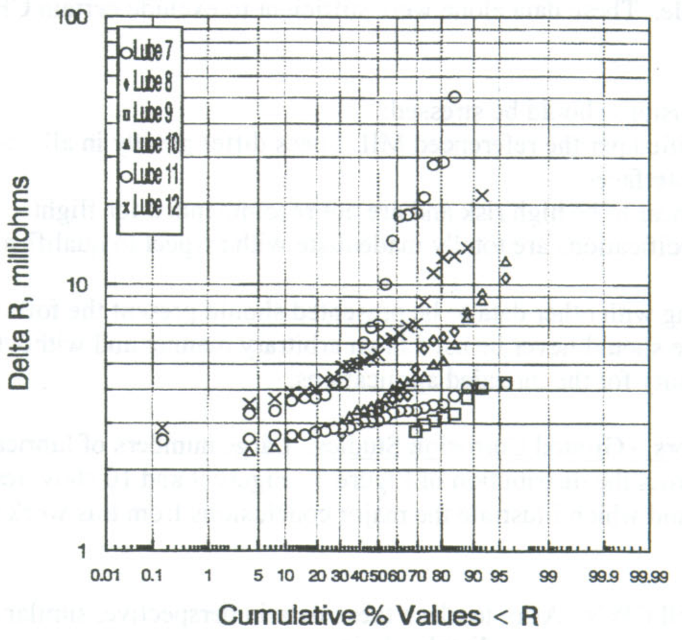

Figure 8. Contact Resistance of Lubricated Gold-Gold Connectors After Thermal Ageing; 80 C, 1000 Hrs

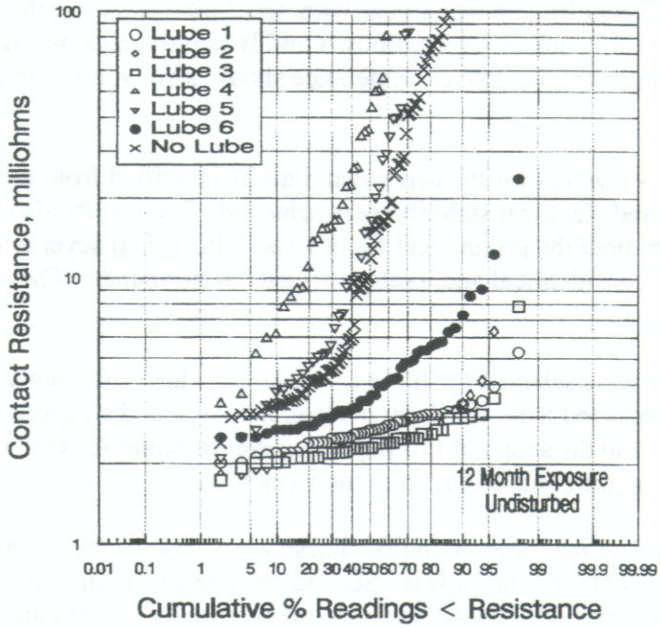

Figure 9. Contact Resistance of Aged Mated, Gold Plated Connectors at Sheltered Seacoast Exposure; Effects of Lubricants (Mil 87177A and 81309E)

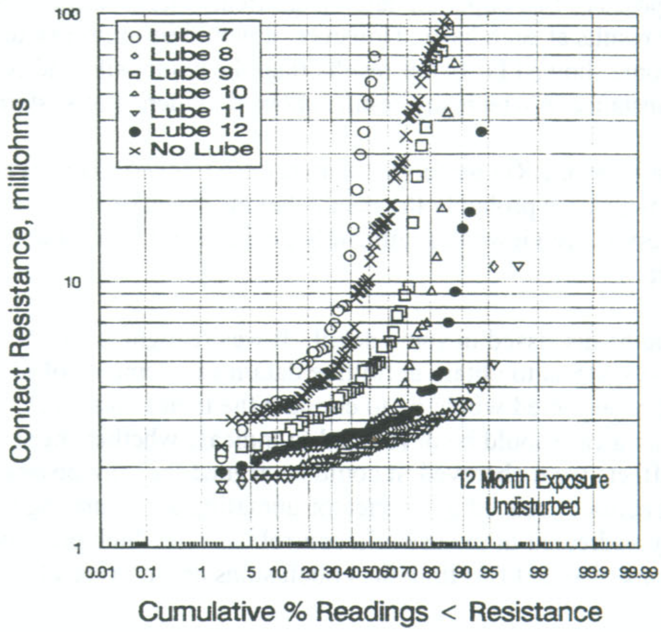

Figure 10. Contact Resistance of Aged Mated, Gold Plated Connectors at Sheltered Seacoast Exposure; Effects of Lubricants (Mil 87177A and 81309E)

Figure 11 shows data for samples exposed 1 year with the 2 lubricants which were eventually selected for flight tests. These particular data were taken for locations A and B as referenced in Figure 3, but we may state that similar results were obtained at all other locations. Reference should also be made to Figure 5 for the data for the untreated condition.

The results in Figure 11 show that for the better materials as identified from the initial qualification program, total corrosion inhibition and electrical stability were achieved. The results also illustrate another conclusion, which was reached from both the ground and flight tests. This is that several materials qualified under both specifications appear to give identical and totally adequate performance. The results do not reveal any bias towards either.

Flight Tests. Two CPCs were selected for flight test studies. These eventually involved upwards of 150 aircraft and a variety of LRUs selected from the flight control, avionics, and weapons systems (3). A discussion of these results is far beyond the scope of this paper. However, some selected data will be shown which we believe will fairly represent the conclusions from the work to date.

Figures 12 and 13 show data for Bases A and B. These were selected for several important reasons. First, they represent independent tests of the 2 lubricants. Second, they represent unique situations in which only a portion of the fleet at each base was treated. Thus, there was an opportunity to compare data for treated and untreated conditions for aircraft in identical environments and operations. At all other bases, the entire fleet was typically treated and in these cases the basis for comparison had to be the rest of the fleet (untreated) by Command.

The data analyses that were done, typically involved tracking LRUs for each base by 5 digit Work Unit Code (WUC). For the purposes of this paper all data for all treated items have been grouped together to present an overall picture for the results at each base. However, it would be appropriate to note that the results differed widely by LRU type. Some showed far better results than the composite and some showed little apparent benefit; however, there was no instance in which any results showed evidence of systems degradation.

There are several measures of LRU performance that were tracked. However, the data in Figures 12 and 13 represent LRU removals which are probably the results having the greatest economic impact from the viewpoint of each base. These results are viewed as uniformly positive and present a strong circumstantial cases for a cause and effect relationship.

The latter point should be discussed in some detail. It was recognized at the outset of this work that it would be impossible on operating systems to obtain definitive data/measurements of the type shown earlier in Figures 4-7. The best that could be expected would be to conduct the treatments, compare data to the untreated conditions, and determine whether a case could be developed to indicate whether there was any effect on performance. Even if positive effects were observed, it could be argued that any observed effects were due to nothing more than the "cleaning actions" caused by connector unmating and remating to perform the lubrication. The latter argument was partially addressed in the use of a control base in which only connector cleaning was performed. Those results were mixed and at this time the conclusions are in favor of a real and positive effect of lubrication.

The conclusion from Figures 12-14 is that there appears to be a very favorable, long term impact of lubrication on systems performance associated with just CPC treatment of I/O connectors on LRUs. These data show results which can be measured in economic terms. However, other analyses show positive effects on reducing intermittent type failures (CND's) and aircraft availability.

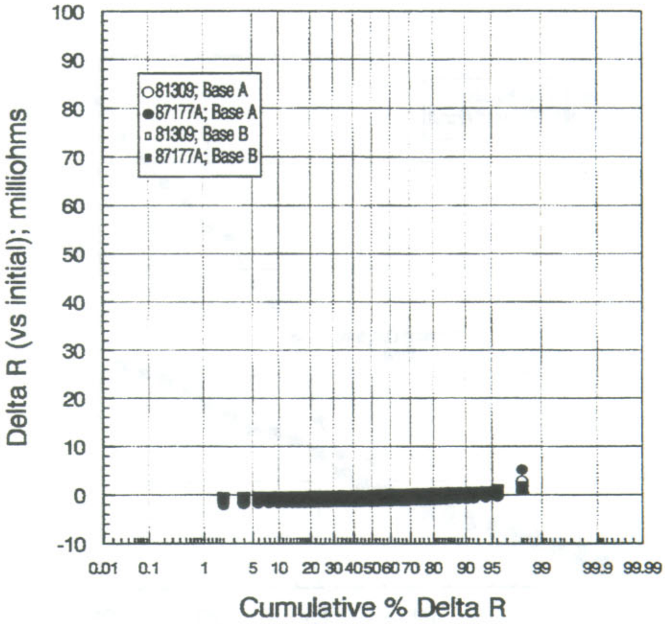

Figure 11. Contact Resistance Change of Gold Plated Connector Test Samples with Lubricants; Two Bases; 1 Year Exposed

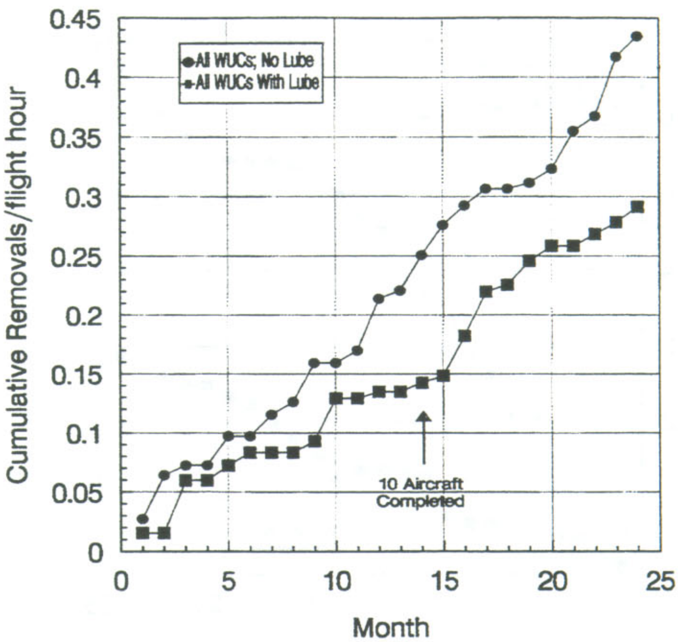

Figure 12. PPS (on) Data for Removals/Flight Hour; all WUCS for Base A with and Without Lube; Month 1 = January 1997

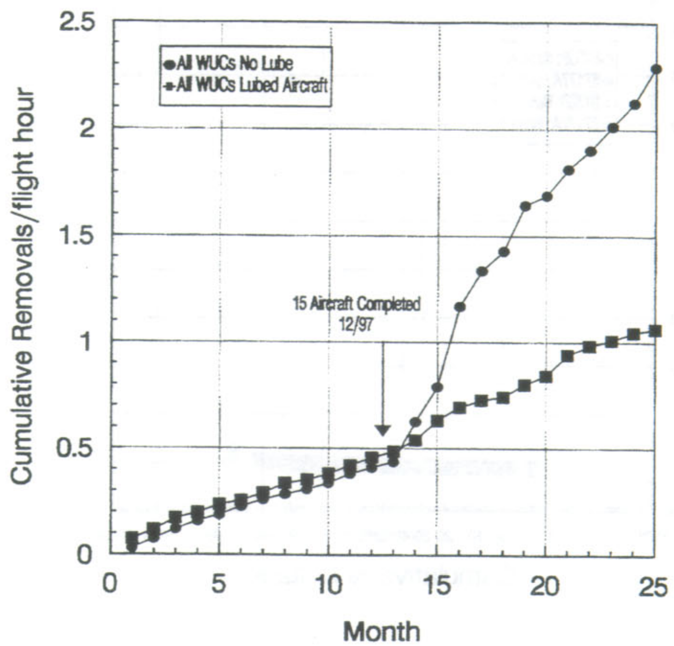

Figure 13. PPS (on) Data for all LRUs; Removals/Flight Hour Base B With and Without Lube; Month 1 = November 1996

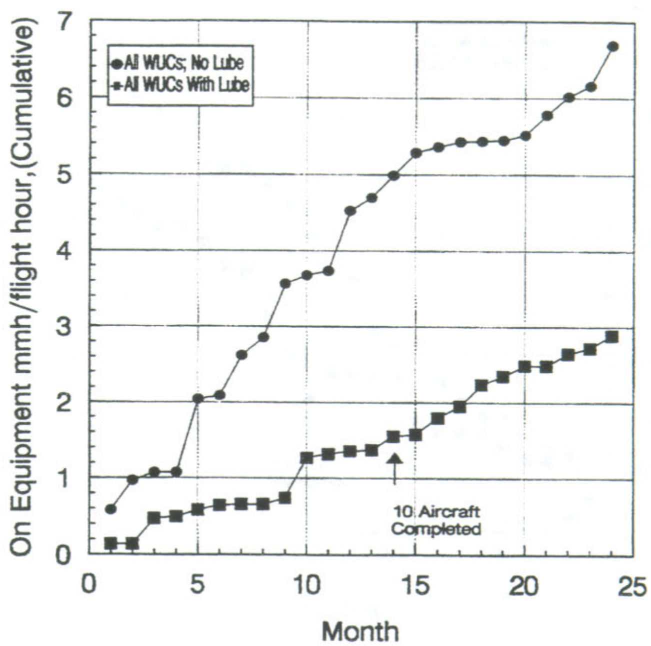

Figure 14. On Equipment Labor Hours for all WUCS for Base A With and Without Lube; Month 1 = January 1997

CONCLUSIONS

This work has demonstrated that it possible to obtain large amounts of corrosion rate data from field sites worldwide in a cost-effective manner. If samples are properly packaged and simple guidelines are established along with good communications with field site personnel, it appears that meaningful data can be obtained in relatively short periods of time (months).

The results from this work have revealed deficiencies in the algorithms, which have been developed for the Air Force to predict field site corrosion rates. The major deficiency is the tendency to greatly underestimate corrosion in those environments of particular concern; i.e. the more severe sites. Whether this deficiency is due to the algorithms or to the available data which are needed as inputs to the algorithms has not been determined.

This work has demonstrated the very high rate of connector corrosion, which can occur in ambient environments if environmental control and/or sealing are not exercised and the ambient environment is allowed to ingress to the electrical interface. The studies have shown that the degree of degradation as measured by contact resistance does correlate well with corrosive severity. While such effects might be expected for severe environments the work has demonstrated similar effects across all environmental severity levels extending downward to the least severe. The practical implication from this is that in all cases the external environment must be excluded from modern electronics and connector interfaces in particular.

The protection scheme which was shown to be very successful in this work was the use of a very few lubricants/CPCs. A few of these materials conforming to MIL-C-87177A and 81309E have been shown to give almost total corrosion inhibition in even severe field environments. At the same time those same materials will survive comprehensive laboratory testing .

Unfortunately this work has revealed severe deficiencies in a number of COTS materials which are presently qualified to these specifications. This indicates that the present specifications need to be upgraded to include more extensive and realistic evaluation of these materials if they are to be used for electronics applications.

Several of the materials, which gave excellent laboratory and ground based field results have now been studied in flight tests on avionics with very positive results. No implementation problems have been reported by field personnel. Performance data tracked over a period of 2 years have developed a strong circumstantial case for performance enhancements, which may translate into substantial cost savings. Initial estimates are that in the extreme the potential savings annually for just the F-16 fleet could approach several hundred million dollars.

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Appendix F

David H. Horne, "Catastrophic Uncommanded Closures of Engine Feedline Fuel Valve from Corroded Electrical Connectors"
(14 pages)

Paper
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CORROSION2000

CATASTROPHIC UNCOMMANDED CLOSURES OF ENGINE FEEDLINE FUEL VALVE FROM CORRODED ELECTRICAL CONNECTORS

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ABSTRACT

The F-16 Fighter is a spectacular combat aircraft that has proven its value, but corrosion problems plague its maintainability, safety, and reliability. One problem discovered by a Kelly AFB Engineer trained in corrosion control was corrosion of tin-plated electrical connector pins mated with gold-plated sockets. Fretting corrosion between these contacts (so subtle that it's not even visible) appears to have been implicated in at least five F-16 crashes when their main fuel shutoff valves closed uncommanded. The prime contractor believed the tin to gold was astute design and incorporated the dissimilar metal combination in connector sets all over the aircraft. However, application of "MIL-L-87177A Grade B; Corrosion Preventive" into the fuel valve's dissimilar metal electrical contacts appeared to stop the uncommanded fuel valve closures for about a year, suggesting corrosion was the cause. In a MIL-L-87177A corrosion test application to all F-16 aircraft electrical connectors increased the *Mission Capable* (MC) rate 16%. In addition, many millions of dollars saved were documented even in the flight test program by treating aircraft and AGE electrical connectors with the corrosion preventive spray.

Keywords: Dissimilar metals, gold contacts, tin contacts, sea water, fretting corrosion, galvanic corrosion, electrical connectors, short circuits, inhibitors, military equipment, aerospace, humidity, F-111, F-16, moisture intrusion, MIL-L-87177A, lubricants, corrosion inhibiting lubricants, corrosion specialist, corrosion costs, corrosion control training.

INTRODUCTION

In the early 1960s the *U.S. Air Force* (USAF) procured a wonderful aircraft that had variable position wings, could function in a variety of weapon mission tasks and promised to have previously undeveloped capabilities that would reduce aircraft vulnerability to enemy ground fire significantly. The terrain following radar allowed the F-111 aircraft to be flown under most radar observation envelopes and fast enough so that it would be past any ground resistance sites before the enemy could respond to its presence. However, instead of always being a terrain following aircraft soon after its emergence, it began being a terrain impacting aircraft. Notwithstanding its many excellent characteristics the Defense Secretary, MacNamara, halted the F-111 production after about 400 were manufactured. The promise of a wonderfully effective weapon system was reduced by the mysterious failures that made the aircraft appear impossible to use safely. Some of the F-111 engineering designs were used in the F-16.

FIELD HISTORY AND TESTING

A new Statement of Need was developed for an aircraft that could fill the Air Force's (AF) defense requirements, and the F-111 manufacturer designed a smaller, lighter aircraft without the exotic terrain following electronics. The new *fly-by-wire* aircraft, chosen from several proposed by different aircraft manufacturers, was very maneuverable, advertised to have only *proven* electronics systems and was named the F-16 Fighting Falcon. The author, a F-16 "*test engineer*" for the beginning of the F-16's operational phase[(1)] (the Multinational Test and Evaluation program 1979-1981), was told that during the initial F-16 aircraft testing some anomalies occurred at Edwards AFB, CA, including, several unresolved uncommanded engine shutdowns (flameouts). In the production phase test program an aircraft on takeoff roll could not gain adequate velocity to take off, so the pilot braked near the end of the runway and returned the aircraft for maintenance inspection. Soon thereafter the F-16 SPO (System Program Office) at Wright Patterson AFB (WPAFB) demanded the contractor correct the causes of the motor operated Main Fuel Shutoff Valve (MFSOV) closing uncommanded. Contractor personnel said that the flameouts had been caused by engine problems or by pilots inadvertently repositioning the valve position control switch, the Master Fuel Switch (MFS), to the *off* (closed) position. The MFS Panel was redesigned with a guard over the MFS to prevent inadvertent movement to the *off* position. To eliminate the possibility of valve closures caused by stray currents in the MFSOV control circuitry, the contractor designed an electronic unit to block stray voltages to the MFSOV which it called "*The Failsafe Module*" (FSM). While a vendor set up a production line and started producing the Failsafe Module the MFSOV was "*wired open*" so that it could not close no matter what, and during that time no such anomalies occurred. After the MFSOV Failsafe Module installation, the MFSOV lock-wire was removed, and AF historical records show the MFSOV closure anomalies began again.

Strange anomalies associated with the MFSOV continued to occur until a Nellis F-16 flew to Carswell AFB in November 1986 for Contractor modifications. The aircraft lost power on final approach and landed on the runway overrun, bounced up onto the runway, and rolled to a stop. A tow moved the aircraft to the contractor's facility. No report was received of the MFSOV position. The engine was changed, the modification was done, and the aircraft was flown back to Nellis AFB. However, the pilots refused to fly the aircraft. So the AF ordered its Fuel System Engineer (FSE) from Hill AFB and the Contractor's troubleshooting expert, Roger Matthews, to investigate the aircraft. The Wing's personnel already had changed out the MFSOV and the failsafe module, but the pilots still would not fly the aircraft. A 388TFW pilot who saw the *near mishap* pilot at the contractor's facility after the engine flameout said, "... the pilot was still white two days later." Both the MFSOV and the failsafe module, a small, about two cubic inch unit that resides on the MFSOV actuator connector, were available for testing and were tested in the Unit electrical shop for anomalies. The MFSOV was tested both with the failsafe module installed and not installed. Note that Base personnel examining the assembly before the investigation team arrived removed the FSM from the MFSOV several times and remated the connectors, which would have wiped off any corrosion products on the pins. The MFSOV operated properly with the module attached, but without the module attached the MFSOV failed. When power was applied to the "*open windings*" pin, pin A, it went to open within four-seconds. With power applied to the "*close windings*" pin, pin B, it seemed to *close* as quickly; but with power applied to both pins A and B simultaneously it went to the *open* position, started to go back toward *close*, stopped after moving about 10-degrees toward *close*, returned to *open*, then "*hunted*" back and forth. After *hunting* for a moment the MFSOV continued toward *close* and stayed there. Even removing power from pin B didn't cause the MFSOV to go back toward open.[(2)] However, jarring the MFSOV a little with a screwdriver handle with power applied to either pin A or to pins A and B simultaneously caused the MFSOV to cycle immediately toward open again. When power was applied to both pins A and B the valve hunted again when it became fully open. This scenario was repeatable with power applied to both pins A and B.

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(1) In the F-16 Suitability Program Electronics Engineer William Frost monitored and analyzed the effectiveness of aircraft and aircraft ground equipment (AGE) computers. The author had responsibility for the rest of the aircraft hardware.

(2) The MFSOV Specification required that the windings to drive the valve to open produce greater torque than the windings to drive the valve closed. Then, the delta torque failsafe condition, if power ever were provided to both the open and close windings, would drive the valve to open. Therefore, with power provided to both pins A and B the valve must go open, and the *"open"* microswitch must open which opens, i.e. stops power to, the *"open"* motor winding circuit. Then, with power to both A and B pins the close windings (excited by power to pin B) drive the valve a short distance toward close until the "*open*" circuit microswitch closes again restoring power to the *open* windings that stop the valve movement toward close and drive it toward full open again. This process is called "hunting."

The MFSOV motor windings have microswitches that open the circuits to interrupt power to the motor after moving the butterfly to fully *open* or fully *closed* position. However, if the microswitch in the circuit used to drive the valve to *open* were to stick in the "*open circuit*" position and at the same time power were applied to the B pin, the motor would drive the valve to *closed.* If the MFSOV then were jarred, such as by a hard landing, the microswitch could become unstuck allowing power to go to the open windings to drive the valve open again. Perhaps that's why no mention was made of the MFSOV on the aircraft landing at Carswell being closed; i.e. it may have opened again if it were closed. Many of the MFSOVs on aircraft which had flameouts have been tested and found to hunt and then drive to *close* with power applied to both pins A and B. See Figure 1. Thus, one potential failure mode was identified.

A 388FW aircraft at Nellis AFB after a morning sortie was preparing to return to Hill AFB, but when the pilot initiated First Start the engine wound up for about 45-seconds and wound down again. The MFSOV was found in the *closed* position. The Master Fuel Switch was verified in the MASTER (open) position and was cycled from MASTER to CLOSED and back to MASTER without any effect on the MFSOV. The harness was removed from the failsafe module and the module was removed from the MFSOV. Some corrosion products were seen among the tin pins in the connectors and in the sockets. However, the troubleshooting procedures were continued including measuring the resistance of the harnesses from the cockpit to the MFSOV failsafe module. When the resistances were established within tolerances the connector was remated to the failsafe module on the MFSOV and the circuit tested. It performed perfectly. The only actions were to disconnect and reconnect the connectors, but the problem was fixed. The F-16 flew to its home base but was grounded until a failure analysis and decision that it was okay to fly were made. Consultation with avionics and electrical servicing personnel about fixing such problems revealed that it was a routine troubleshooting procedure not only on the F-16 but on other equipment to simply disconnect and remate the electrical connectors. The theory proposed[3] for the effects on the system was that the corrosion products seen in the connector were holding the connector contacts apart thus preventing good electrical contact or causing high resistances and preventing adequate electrical current to perform its function. Analog circuits are especially vulnerable to high resistances. The simple removal and remating of the connector parts wiped the interfering salts created by the corrosion away from the contacts so adequate electrical contact could be made. Another phenomenon proposed was that the corrosion product salts falling to the bottom of the connector (positioned with a normally horizontal bottom) could collect moisture and create an electron bridge between both the +28-volt electrical pins A and C causing a short to pin B between them. A report of extensive corrosion in a vertically positioned failsafe module connector found after a ground flameout in Florida indicated water (probably condensate from high humidity in the air due to many changes in altitude lowering and raising air pressure) was puddled in the bottom of the connector. The combination of the previously mentioned incidents raised the situation to the General level from which it has not abated. A Tiger Team was appointed and a conference to brainstorm the problem was held. Action items included an improved MFSOV system maintenance checkout procedure, altering the MFSOV requiring new microswitches to be installed at overhaul, all Field Units to report MFSOV system anomalies immediately to the System Manager, and to impound the aircraft until a resolution was made. The improved maintenance procedures began identifying previously undetected MFSOV problems so a call or two per day began coming in. SA-ALC began watching the connector condition of MFSOV actuators returned for overhaul and sent the FSE a badly corroded connector from which pins B, C and D were corroded away.

Some ground and a few airborne flameouts continued to occur which heightened everyone's anxiety. An aircraft in Europe at 1500-ft MSL lost power and began to loose altitude, so the pilot followed the restart procedure without success. Within seconds the aircraft fell to about 800-ft; the pilot declared an emergency and prepared to bailout only to realize a town was directly in front of him. It is impolite, at least, to land one's aircraft in a town after bailout, so the pilot turned the aircraft while trying to restart. During the turn the aircraft shuttered (perhaps from wind movements), and when he was about to pull the ejection ring, the engine accelerated recovering the aircraft. The pilot landed at a nearby airport. The MFSOV and failsafe module connector examination revealed corrosion products in both.

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[3] Metallic corrosion (oxidation) produces reaction products (often salts) that require greater volume than the original metals. The corrosion products between the pins and the sockets push the electrical contacts apart reducing the conductivity areas, increasing electrical resistance or causing an open.

A similar incident occurred with a U.S. F-16 based near the ocean on a *functional check flight* (FCF), which is required after certain maintenance procedures to check out control systems. The FCF started out normally with a fast takeoff and a vertical climb, but at about 1500-feet the engine lost power. The pilot immediately leveled the aircraft and attempted a restart which was successful, but obtained only 79% RPM, barely enough to keep the aircraft flying. While attempting a normal turn it lost altitude, so level turns, which are slow, were made. The pilot tried to get in line to land at the airport of the nearby city but could not maneuver to the proper runway approach. Instead, he flew over the city at about 800-ft between a smokestack and a radio tower and eventually was able to maneuver to land at another airport. Unfortunately a maintenance crew immediately serviced the aircraft, so the MFSOV condition and position could not be established, however when the AF engineer laboratory tested it at Kelly AFB it repeatedly failed closure tests. Another aircraft from the same base had to brake near the end of the runway to avoid the barrier, because it could not get enough power to take off. The pilot taxied back to the engine shop and the MFSOV butterfly was found in the near closed position[4] such that only a small amount of fuel could pass to the engine.

The AF funded the contractor to investigate the MFSOV control circuitry, study the numerous problem reports and determine what must be done to correct the uncommanded MFSOV closures. After an extensive study the contractor reported there was no conceivable way that anything could go wrong with the MFSOV system. In that report to show the excellent manner in which the MFSOV system was designed the electrical connectors of the MFSOV, the failsafe module, and the harness were identified to have tin plated pins and gold plated sockets. The Kelly AFB engineer responsible for the MFSOV and the FM that was attached to it had completed the DoD Corrosion Control Training given by the Rock Island Arsenal noticed in that report that the electrical connectors had dissimilar metal contacts. Subsequent investigation revealed that many connectors on the F-16 had the tin pin to gold socket arrangement.[5] At least the AF engineers who'd been trained in corrosion control believed they knew why corrosion products were seen in malfunctioned MFSOV connectors. But a microscope or magnifying glass sometimes was needed to see the corrosion products or the pin damage that caused malfunctions. The EMF between gold and tin on the galvanic scale is 1.826 volts, enough to make the connector a fine battery (See Table I). Also, pin B was chosen to provide power to drive the MFSOV closed, and pins A and C are energized with +28-VDC when the MASTER FUEL SWITCH is at MASTER and the MFSOV is *open*. This type of pin placement design error caused the short circuit that interrupted NASA's Mercury 9 space shot on its 22nd orbit, and Navy Commander G. Gordon Cooper was extremely lucky to have returned safely. Cooper while drinking a little water spilled a tiny bit which spread throughout the capsule in its weightless orbiting condition, and some entered the connector and shorted the connector.

Lloyd O. Gilbert, the DoD's premier corrosion consultant and NACE Corrosion Specialist, was called about the connector corrosion. He recommended contact with AF Materials Lab corrosion scientist, Fred Meyer, a NACE Corrosion Specialist. Mr. Meyer was working with a newly identified corrosion inhibiting lubricant originally developed by the Bell Labs that was available commercially. Gilbert said it might be helpful to prevent the corrosion recognized in the MFSOV electrical connectors. Fred Meyer incorporated the corrosion inhibiting lubricant's pertinent physical characteristics into a new specification, MIL-L-87177. A *national stock number* (NSN) for the formulation was assigned, and the corrosion inhibiting lube was obtained for use. The F-16 *System Manager* (SM) issued a *safety time compliance technical order* (TCTO) in September 1989 with a 90-day suspense to accomplish the electrical connector treatment. Within a few weeks from the time the TCTO was issued the stream of calls reporting MFSOV incidences stopped. Then one came in December, but its MFSOV connectors had not been treated. Again in about May 1990 some calls started again. However, it was later determined that some field units must have used unauthorized lubricants, because at least one of the aircraft crashes mentioned later was from a base that had not obtained the designated lubricant. Therefore, at some bases the seven months of grace may have been due to dismating the connectors and the assisted wiping and the temporary lubrication of a certain inferior lubricant known to be available which contains olefins that polymerize and form gums. The aircraft of another significant incident not herein described had been classified as having been treated *in accordance with* (IAW) the TCTO but the crew chief revealed he only had been briefed verbally on how to do the TCTO and never read it. Thus the TCTO probably was not complied with. So some MFSOV connector treatments may have been marginal at best. An improved lubricant inhibitor package caused a revision to MIL-L-87177A with a Grade B (Ref 1). The F-16 Technical Orders require the newer formula for treatment in MFSOVs, failsafe modules, and certain other places on the F-16s at intervals of about every year.

After a ground flameout in Denmark the MFSOV was sent to the FSE for examination. With the naked eye no significant defect was seen in the MFSOV actuator connector, but a 10X stereo microscope revealed a thin thread of gold lying between

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(4)This may have been like the Multinational Operational Test & Evaluation (MOT&E) Program incident.

(5)David Sanders, Ogden F-16 Electronics Engineering Team Chief (circa 1985), was able to change the design of many of these gold-tin connector sets to gold-gold for production aircraft but missed the MFSOV, brake control valve and many other connectors.

and touching both A and B pins. Gold is a superior electrical conductor, and even the thin gold strip may have had enough conductivity to allow enough electrical current to move the MFSOV slowly to close. In addition, that actuator and some observed later revealed considerable modeling of the tin pins in the area where the gold plated sockets contacted the tin. The gold sockets were not as long as the pins and do not seat to the bottom of the pins. The diameters of the corroded tin pins were distinctly smaller in the socket contact areas than the bottom part of the pin's length. No such pin diameter change was seen on new connectors. It appears the tin pin corrosion impeded the needed power to the MFSOV's *open* motor windings.

The F-16 SM placed the Battelle Columbus Labs on contract to examine the MFSOV system to identify the failure modes. After examining the overall system design and many MFSOV parts, the Battelle scientist reported that the observed corrosion in the electrical connectors was caused by fretting corrosion which in combination with unreliable and silicone contaminated microswitches in the MFSOV actuator is certain to be causing the actuators to be on the verge of failure or in a failed condition constantly. Uhlig defined fretting corrosion as "Damage occurring at the interface of two contacting surfaces, one of both being metal, subject to slight relative slip." (Ref 2)

Corrosion of tin is inherent in an oxygen atmosphere. The mere presence of oxygen contacting tin will cause instant oxidation to SnO_2 which forms a protective film over the tin that is like the instantaneous oxidation of aluminum to Al_2O_3. An essential environmental factor for fretting tin is vibration that wipes the lightly adhering, protective SnO_2 film away from the interface of the contacting surfaces. Obviously the removal of the SnO_2 protective film results in immediate oxidation of the newly exposed tin to create more SnO_2 protective film and allows rapid removal of the tin. The increased volume of the Sn to SnO_2 is a factor in the resultant pitting to relatively great depths. The primary and essential causes of tin fretting include closely fitting parts that are vibrated such that slipping of the part adjoining the tin can sweep the SnO_2 film away. The requirement for moisture present for this reaction either is so small that it is imperceptible or does not exist, but damage is less in moist air compared to dry air possibly due to a slight oxygen occlusion on the tin surface. Other factors recognized to accelerate the rate of fretting corrosion are a moderate increased normal force that still allows movement at the interface, increased damage as temperature is lowered (thus it is not electrochemical), and the damage rate is affected by certain material characteristics of the opposing surface. An increase in vibration frequency for the same number of cycles decreases the corrosion damage which probably is a function of the speed at which a new layer of SnO_2 can be formed. Uhlig notes that fretting corrosion of electrical contacts causes increased electrical resistance between the surfaces that become and remain high resistances. (Ibid, Ref 6) It is wise to test proposed materials for which literature is not available. To inhibit fretting corrosion, complete occlusion of oxygen generally is impractical. However, lubrication generally is an adequate although an incomplete remedy to occlude oxygen from the tin. Lubrication also reduces or eliminates the removal of the existing SnO_2 from the tin surface. Again testing is wise to identify an adequate lubricant for the given system and environment.

Although some corrosion damage or corrosion products have been seen in the MFSOV connectors, Battelle warned that the fretting corrosion of tin is surprisingly subtle such that the tin contacts can be sufficiently corroded to have a high electrical resistance even when no corrosion damage or products are noticeable. Tin electrical contact corrosion makes the parts at risk electrically; i.e. high resistance, although one may not be able to see anything dramatic or awry. Thus, unless a corrosion preventive is employed, tin electrical contacts always must be assumed to be corroded to the point of impending or at failure and to have been so before dismating and examination even if they appear to be perfectly okay.

Not all MFSOV uncommanded closures have been warnings or close calls. An F-16 ferried along the southern states to its Gulf home base lost power and crashed within a mile of its runway. The MFSOV was found in the wreckage in the near closed position. No other problem could be found, but it was learned the owning unit had not ever had the corrosion inhibiting lubricant specified by the TCTO and subsequent technical orders (TOs).
A pilot in a two ship sortie on a routine mission from a Pacific Base reported an engine power loss to his flight lead. He tried a restart unsuccessfully. The pilot looked at and felt the Master Fuel Switch to assure it was in the MASTER (open) position and cycled it to OFF (closed) and back to MASTER. Another attempted restart and other emergency procedures were attempted without success. The flight lead then ordered him to bail out. The MFSOV was found in the near closed position (butterfly against the seal-not fully on the seal).

A few months later another F-16 on a FCF lost power on takeoff from a plateau airfield and crashed. Its MFSOV was sent to the *AF Materials Laboratory* (AFML), and the AFML scientists wrote a report stating the MFSOV had been in the near closed position when the aircraft it was in crashed and burned.

Another aircraft being ferried along the eastern seaboard lost adequate power to keep aloft so the pilot declared an emergency and was told to land at a certain nearby airport. That airport was too short, and the aircraft slid off the end of the runway across a highway immediately in front of a fuel tanker. The MFSOV again was found in the near closed position.

Immediately after a crash in Florida an AF Fuel Shop team was sent to recover the *Emergency Power Unit* (EPU) fuel tank and other parts that could be hazardous to investigating personnel and was told to determine the MFSOV position. That team found the MFSOV closed or near closed.

Several F-16s had engine flameouts and crashed before MIL-L-87177A's use was required, but although suspect, adequate information is not available to prove a definite relationship with MFSOV malfunctions. Some F-16s are being operated with the MFSOV wired open again. But, the TOs require regular connector treatment at specific inspections, so the few MFSOV anomaly reports make it appear the connector treatment is mitigating corrosion on the aircraft that are not wired open.

Another ground incident caused criticism for the MFSOV gold to tin connector causing corrosion and uncommanded valve closures. The Contractor accomplished some testing that demonstrated that under certain conditions vibration could open the locking mechanism and together with high fuel flow could cause the MFSOV butterfly to move toward close. It also claimed MIL-STD-889 *required* the use of tin to gold in connectors.(6) However, no testing proved the MFSOV closed that had correct power to the open windings. After the failsafe module failed to stop the uncommanded closures (circa 1984) the contractor obtained a second vendor to make MFSOVs. But, the Contractor instructed the new vendor to use the same tin pin connector on its actuator.(7) The new vendor designed its own double roller locking clutch and failsafe circuitry which it installed within its actuator case. Thus they avoided any gold to tin connector corrosion between the MFSOV and the module. The Contractor stopped installing the original vendor's MFSOV on new aircraft, so the quantities of original and new vendor MFSOVs are about equal. But, in contrast with aircraft using the original MFSOV (which generated easily 200 trouble calls to the author's office plus those in USAF computer records) only two reports are known on the second vendor's MFSOV. After the first crash some fuel flow testing was done that showed high fuel rates, >24000-*pounds/hour* (pph), could produce a force toward close on the butterfly. Normal cruising fuel flow is about 4,000-pph and military power is about 8,000-pph. Augment uses about 39,000-pph, so aircraft taking off could use that much fuel but not landing or ferrying. If a stuck microswitch or corrosion blocked electric power and the locking mechanism unlocked (never proven to happen from aircraft vibrations) the original vendor's valve might move toward close in augment.

Since the connector difficulties appeared to persist, the FACTS Office (Fasteners, Actuators, Connectors, Tools, and Subsystems) at Wright Patterson AFB, OH funded an extensive test program with Battelle to determine the effectiveness of many lubricants being used in Air Force weapon system electrical connectors. Battelle performed laboratory testing; field testing of the lubricants' corrosion inhibiting abilities at numerous military bases and industrial test sites; and finally in aircraft ground equipment (AGE) and treatment of F-16 electrical connectors with extensive monitoring. Laboratory testing of specific connectors used on the F-16 was done to identify the corrosion modes, to determine the active laboratory testing; field testing of the lubricants' corrosion inhibiting abilities at numerous military bases and industrial test causes, and to

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(6) MIL-STD-889 that *allowed* tin to gold in certain places has been changed to prohibit tin to gold contact.

establish corrective measures to inhibit or prevent continued corrosion. It was accomplished with three axis vibration at known aircraft frequencies. Sets of connectors were vibrated either with or without lubricant, without lubricant for initial effect observation and then lubrication, and testing other parameters to determine what circumstances inflict damage to the connector contacts (thermal aging, rapid thermal cycling, and temperature/humidity cycling). Damage for this program was defined as effects causing increased electrical resistance. The two-year field test revealed some of the lubricants touted to be corrosion inhibitors actually accelerated corrosion, but two were outstanding corrosion inhibitors. One of them qualified to MIL-L-87177A, Grade B. Unprotected test panels at some sites incurred a rust bloom in one day, but the panels protected by MIL-L-87177A Grade B showed no corrosion at the end of the two-year test (Ref 3).

Laboratory tests confirmed that vibration was the major stress, which was responsible for the degradation of the electrical contacts and the increased electrical resistance. Vibration of unlubricated connectors for 20-days to represent 480-hours of aircraft operation, which is equivalent to about 1.5-years of aircraft flying, resulted in severe contact damage as measured by as much as 275 times the electrical resistance. The lubricated connectors showed almost complete inhibition of the failure process. The most encouraging results of the lab testing was that even after severe fretting corrosion damage to connectors, the lubrication treatment to the connectors restored their conductivity distributions to a level close to the initial/nondegraded state. Thus it appears that treatment of connectors known already to have been subjected to years of fretting corrosion with MIL-L-87177A Grade B can restore their capacities to a near new condition.

Fretting corrosion of the connectors in the aircraft was demonstrated to put the unlubricated contacts in a failed condition within the test parameters representing 20 to 30 flight hours or for some military units within three months showing an increased resistance of about 250 times as great. After a year the contacts became at a high- risk condition with as much as 300 times the resistance, and in two years a very high probability of a failed state with about 500 times the resistance. The lubricant delayed but did not prevent the fretting corrosion entirely, however the 3-month and six month data revealed almost no degredation. The flight testing at one Base where ten aircraft on which the electrical connectors throughout the planes were treated (the only Base which performed this test) showed a greater than 16%, sixteen percent, improvement in mission capability (MC) for the next year in comparison with the rest of that Base's aircraft, a spectacular improvement (Ref 4). But fretting corrosion does not account for all the damage seen to the connector pins. It appears after the fretting has removed at least some of the tin, galvanic corrosion to the base metal occurs, because iron oxide has been observed around the bases of the pins in some connectors. In fact, severe corrosion to the pins' base metals has been sufficient on some actuators that the pins have corroded or broken off as already noted and shown in the lecture.

On 18 June 1999 a confirmed, uncommanded closure occurred on an aircraft during an engine test on the ground while the MASTER FUEL SWITCH was wired in the MASTER = OPEN position precluding the common idea that the pilot or operator inadvertently flipped the switch to OFF. The contractor referred to it as the first, confirmed, uncommanded MFSOV closure. However, when a team arrived to investigate the impounded aircraft the MFSOV would not operate to either *open* or *close* by electric power. A test on that aircraft to repeat the engine test scenario during which the MFSOV moved toward close was done in September 99 to determine if vibration and fluid flow may have been a factor, but no MFSOV movement occurred. The incident continues under investigation.

Since the MFSOV originally was used on the F-111, the F-111 Fuel System Engineer at McClellan AFB was asked if the MFSOV tin connector pins mated with gold plated sockets. The report received was that not only were the MFSOV tin pins mated to gold contacts but also tin to gold connectors were used all over the F-111. They also had found MFSOV valves in the near closed position and had done vibration testing but had not recognized corrosion problems with the connectors. However, The F-111 had two engines with separate MFSOVs, and the probability of both MFSOVs going closed at the same time was very small. No F-111 loss was attributed to the MFSOV closing uncommanded.

The F-111's circa 1960 technology was primarily analog electronic controls. Analog signals impeded by high resistances can be misinterpreted by associated electronic devices. The F-111 crashes that killed crews may have been caused by erroneous signals from the aircraft's ground following radar to the flight control electronics. To further accentuate that F-111 connector corrosion probably was a problem, replacing some *F-111 analog* line-replaceable units (LRUs) with *digital* LRUs significantly improved the reliability for those avionics LRUs. Comparing the F-16 aircraft MC improvements by treating its connectors with MIL-L-87177A Grade B (many of which are tin to gold like the F-111) it is not surprising that cost studies revealed the F-111 had among the highest avionics maintenance costs per flight hour of any USAF weapon system.

CONCLUSIONS

Fretting corrosion of the tin and the possibility of galvanic corrosion in the electrical connectors of the F-16 MFSOV between the dissimilar metals have been identified as sources of connector corrosion. Fretting corrosion was found to be so subtle that connectors that were in electrically failed condition were noted to appear undamaged. However, severe, probably galvanic corrosion that even caused fracture of the pins was observed. Fretting corrosion of the tin contacts that was so subtle that it could not be seen by the naked eye caused high electrical resistances that effectively caused open circuits. In addition, the corrosion products of the corroded tin and steel pins provides a potential conductivity path between pins A to B and C to D that may be adequate to drive the MFSOV to close. A corrosion inhibiting lubricant spray, MIL-L-87177A Grade B, has been identified and is used annually as an interim fix. Treatment of electrical connectors with the MIL-:L-87177A Grade B was so effective in restoring the conductivity of the tin plated pins and preventing continued corrosion that in a test at one Base the aircraft so treated demonstrated a 16% improved mission capable (MC) rate. In addition, millions of dollars saved by cost avoidances were documented by treating the aircraft and *aircraft ground equipment* (AGE) connectors.

The bottom line for manufacturers of metal products and for government or other purchasers of vendor products is to have competent corrosion scientists participate in the design phase to assure the products can survive their use environment. Many imagined astute design circumstances have caused the destruction of otherwise marvelous products. Persons assigned to be corrosion engineers must be expert in metallurgy and chemistry and trained in corrosion prevention methods. Unknown situations should be tested by suitable scientific tests. Management should assure design engineers have corrosion control training to be able to prevent disasterous circumstances in their products and to recognize mysterious corrosion that occurs even though designs are carefully evaluated. Fortune 500 companies don't automatically produce failure free products. The loss of the five highly suspect F-16s amounts to an expense of more than $100-million. The contractor's costs and losses may have been high, too.

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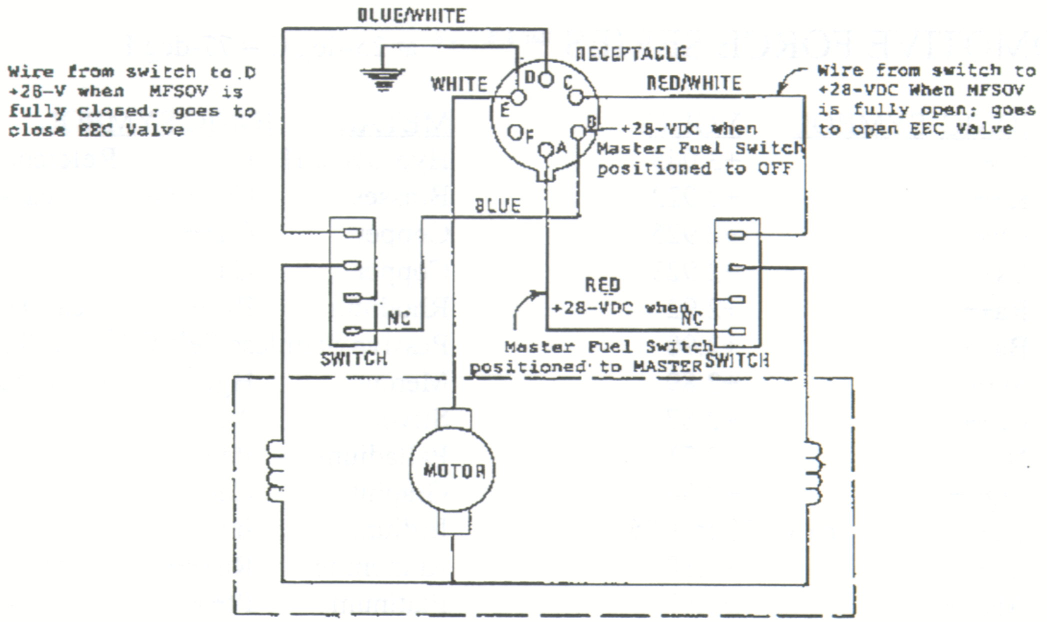

FIGURE I MFSOV INTERNAL WIRING SCHEMATIC TO MOTOR WINDINGS
+28-VDC to pin A from Master Fuel Switch in MASTER position to drive MFSOV to OPEN. Then Microswitch A opens. +28-VDC to pin B from Master Fuel Switch in OFF position to drive MFSOV to CLOSE. Then Microswitch B opens.

Figure I.

ELECTROMOTIVE FORCE SERIES [Ref 5, 6, 7 & 8] 25-deg C

METAL	SYMBOL	VOLTS	METAL	SYMBOL	VOLTS
Lithium	Li^+	+3.045	Cadmium	Cd^{+2}	+0.402
Potassium	K^{+2}	+2.922	Indium	In^{+3}	+0.340
Rubidium	Rb^+	+2.925	Thallium	Tl^+	+0.336
Cesium	Cs^+	+2.923	Cobalt	Co^{+2}	+0.277
Radium	Ra^{+2}	+2.92	Nickel	Ni^{+2}	+0.250
Barium	Ba^{+2}	+2.90	Molybdenum	Mo^{+2}	ca +0.2
Strontium	Sr^{+2}	+2.89	Tin	Sn^{+2}	+0.136
Calcium	Ca^{+2}	+2.87	Lead	Pb^{+2}	+0.126
Sodium	Na^+	+2.712	Hydrogen,	H-H^+	Reference 0.0
Magnesium	Mg^{+2}	+2.34	Brasses	$Cu^{+2}Zn^{+2}$	ca -0.0to0.3
Beryllium	Be^{+2}	+1.70to1.85	Copper	Cu^{+2}	-0.345
Uranium	U^{+3}	+1.80	Copper	Cu^+	-0.522
Aluminum	Al^{+3}	+1.67	Rhodium	Rh^{+2}	ca -0.60to0.8
Titanium	Ti^{+2}	+1.63	Passive SS	Fe^{+2}/Cr^{+3}	ca-.60to.80
Zirconium	Zr^{+4}	+1.53	Mercury	Hg_2^{+2}	ca-0.789to0.799
Manganese	Mn^{+2}	+1.05	Silver	Ag^+	-0.799
Vanadium	V^{+2}	+1.18	Palladium	Pd^{+2}	-0.83
Niobium	Nb^{+3}	ca+1.1	Graphite	Carbon	-0.90
Selenium	Se^{-2}	+0.78	Iridium	Ir^{+3}	-1.00
Zinc	Zn^{+2}	ca +0.762to1.10	Ruthenium	Ru^{+2}	ca -0.8to>1.0
Chrome	Cr^{+3}	+0.71	Platinum	Pt^{+2}	ca-1.2
Gallium	Ga^{+3}	+0.52	Gold	Au^{+2}	-1.42
Tellurium	Te^{+2}	+0.51	Gold	Au^+	-1.68
Iron & Steel	Fe^+	+0.44	Fluorine, 2F	F_2	-2.85

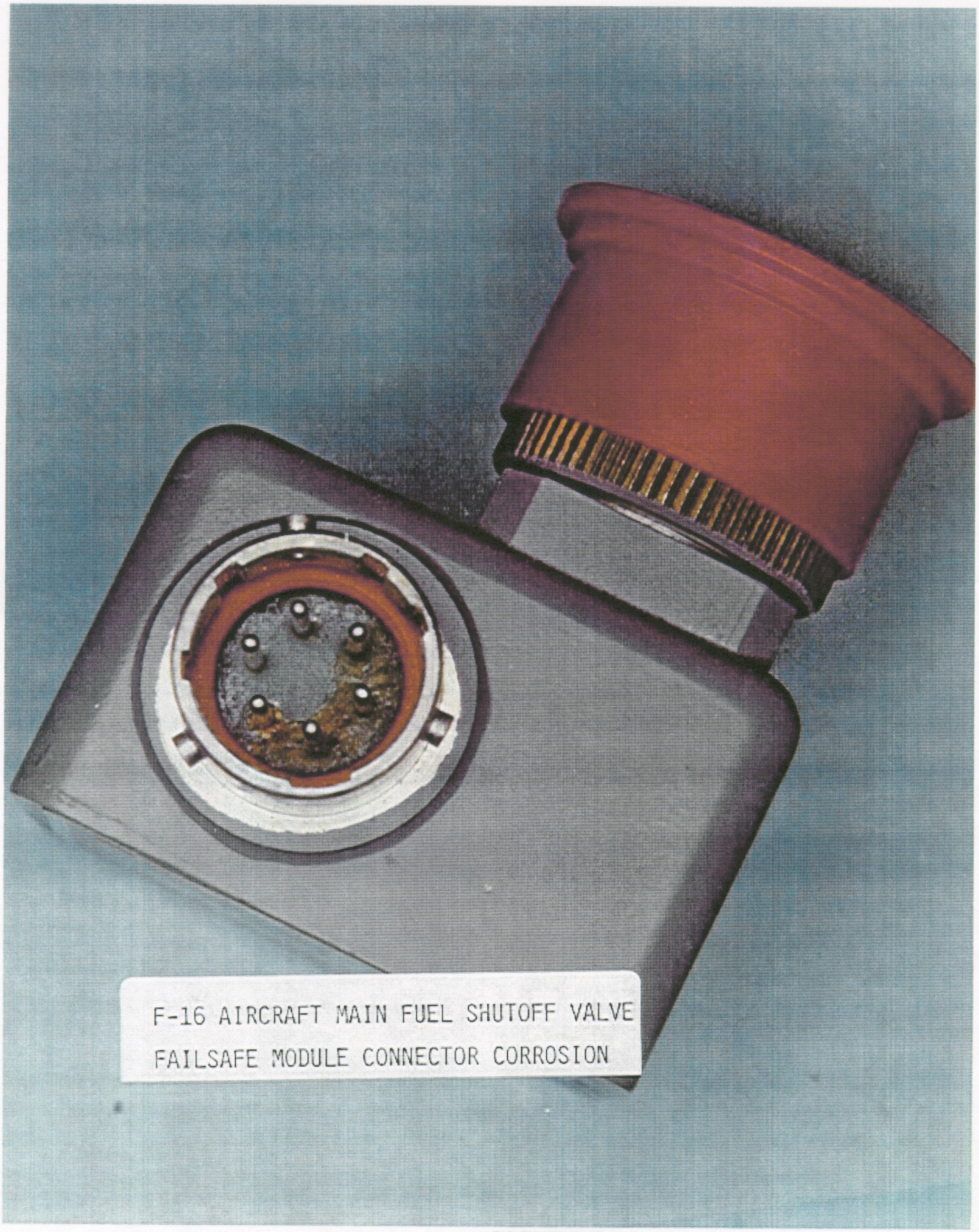

FIGURE 2
TIN PLATED PIN CORROSION IN FAILSAFE MODULE CONNECTOR ON F-16 ACTUATOR FOUND IN THE CLOSED POSITION WITH MASTER FUEL SWITCH TO MASTER

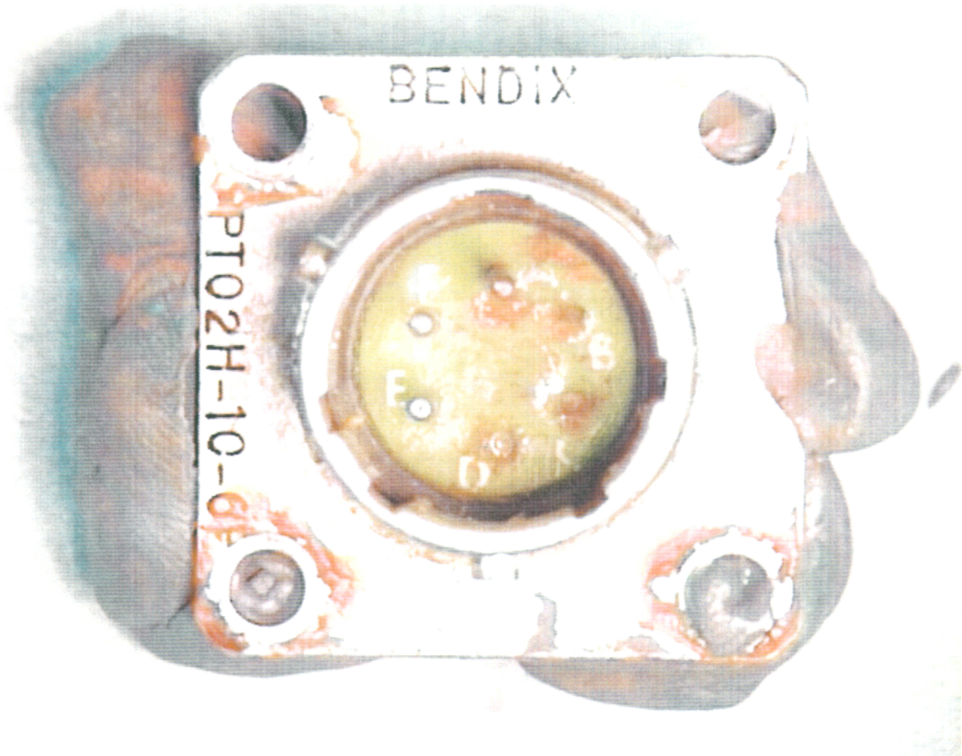

FIGURE 3
Three of Six Pins Missing from a MFSOV Actuator Connector that was sent to the SA-ALC Actuator Overhaul Shop. All Actuator Connectors on the MFSOV Actuators now are Replaced at Overhaul due to Degraded Condition.

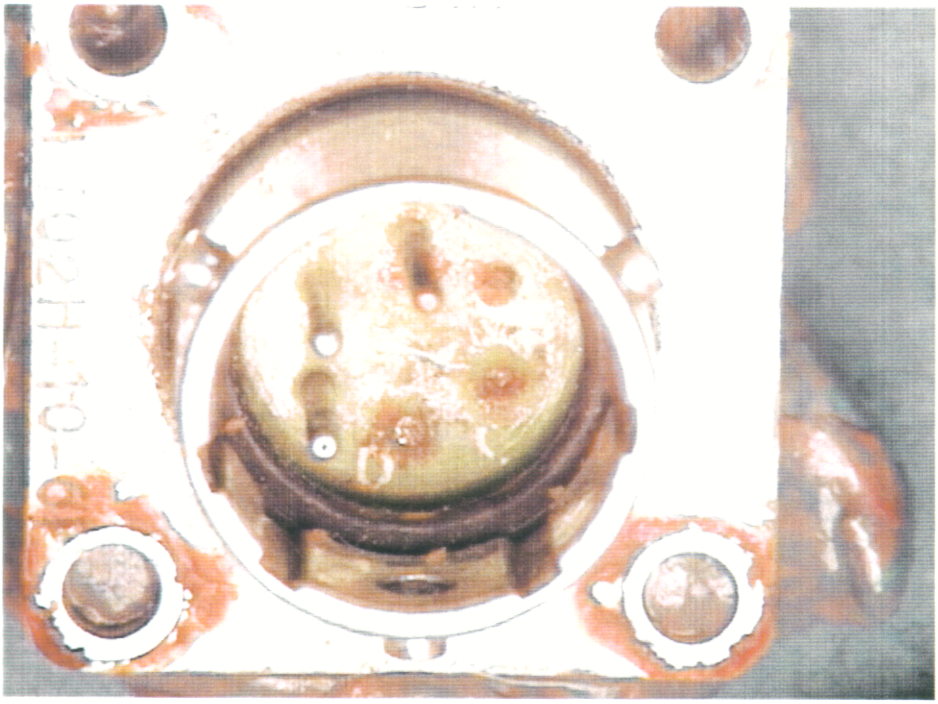

FIGURE 5

Same Connector as Shown in Figure 3 and 4 but from a Slightly Different Angle to Accentuate the Corrosion Damage to the Tin Plated “52 Alloy” Nickel-Iron Pins by Loss of Half the Pins. Note in this View the Iron Oxide on Most of the Cross Section of the Missing Pins Except for Small Spot(s) on the Surface of two of the Pins from which the Pins Apparently Broke Off with some Slight Mechanical Stress.

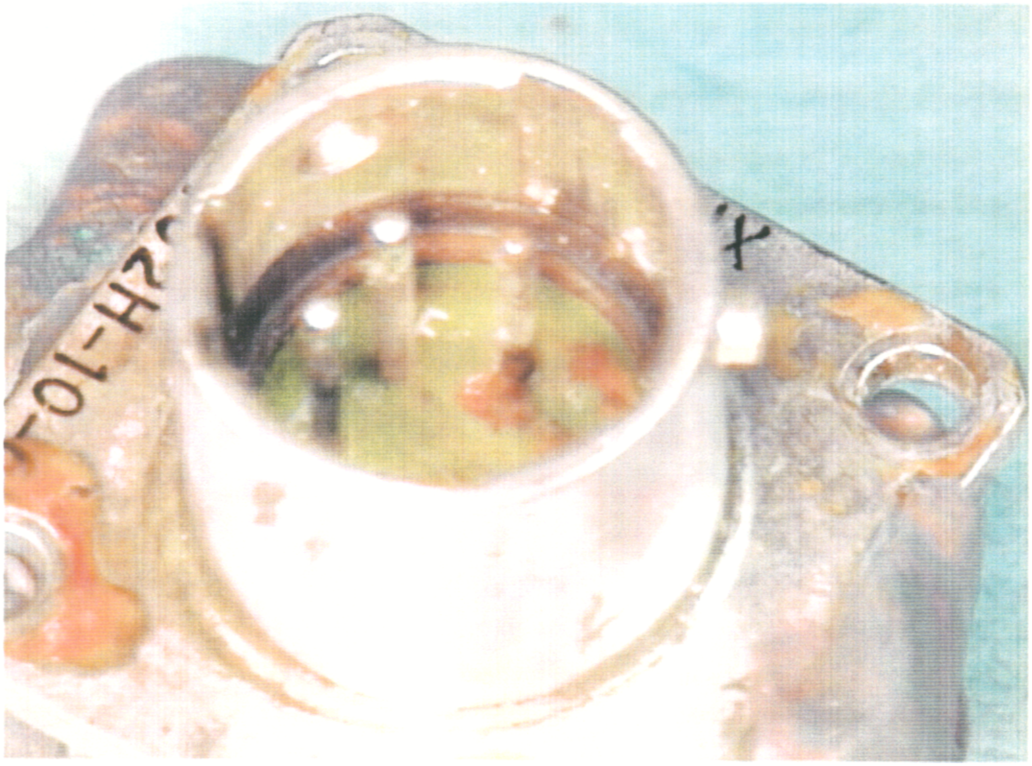

FIGURE 6

The Same Connector as Shown in Figures 3, 4, and 5 but from a Slightly Different Angle to Accentuate the Corrosion Damage to the Tin Plated Pins by Loss of Half the Pins. Note in this View that Pin A is Badly Corroded Near the Base of the Connector.

Appendix G

Neil Aukland and James Hanlon, "MIL-L-87177 and a Commercial Lubricant Improve Electrical Connector Fretting Corrosion Behavior."
(9 pages)

Paper
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CORROSION2000

MIL-L-87177 AND A COMMERCIAL LUBRICANT IMPROVE ELECTRICAL CONNECTOR FRETTING CORROSION BEHAVIOR

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ABSTRACT

We have conducted a fretting research project using MIL-L-87177 and a Commercial Lubricant[1] on Nano-miniature Connectors. Fretted without lubricant, individual connectors first exceeded our 0.5 ohm failure criteria from 2,341 to 45,238 fretting cycles. With additional fretting, their contact resistance increased to more than 100,000 ohms.

Unmodified MIL-L-87177 lubricant delayed the onset of first failure to between 430,000 and over 20 million fretting cycles. MIL-L-87177 modified by addition of 1 micron Teflon powder[2] delayed first failure to beyond 5 million fretting cycles. Best results were obtained when the modified lubricant was used and also when both straight and modified lubricants were poured into and then out of the connector.

The Commercial Lubricant delayed onset of first failure to beyond 55 million cycles in one test where a failure was actually observed and to beyond 20 million cycles in another test terminated without failure. The Commercial Lubricant recovered an unlubricated connector driven deeply into failure, with six failed pins recovering immediately and four more recovering during an additional 420 thousand fretting cycles. MIL-L-87177 was not able to recover a connector under similar conditions.

INTRODUCTION

This work was undertaken to provide information for systems designers at Sandia National Laboratories who want to understand the effects of vibration-induced fretting corrosion in a flight environment on miniature connectors.

Fretting corrosion is due to micro-motion at a connector's interface and is a primary mechanism that can cause connectors to fail under vibration. If the microscopic movement between mated connector surfaces exceeds 20 to 30 microns, the high points (asperities) of the adjacent connector surfaces that are in actual contact will move far enough so that individual contacts are broken and others established. As the number of fretting cycles increases, material from the metallic surfaces may be eroded. This effect is similar to rubbing two pieces of sandpaper against each other. The loosened material chemically reacts (unless the loosened material is gold) with atmospheric gases and forms nonconductive debris. As the number of fretting cycles increases this nonconductive material will accumulate and cause the electrical resistance of the contact to increase and become erratic.

During the tests conducted in this research project, Nano-miniature Connectors of interest to Sandia designers were subjected to controlled fretting conditions. The contact resistance of these connectors was monitored throughout each test. We found that the range to the first detected failure in connectors fresh from the manufacturer was as few as 2,341 fretting cycles and as many as 45,238 cycles. When we treated the connectors with MIL-L-87177 lubricant, the number of fretting cycles to first failure observed in four experiments was 430,097, 1,775,024, 3,015,873, and greater than 20 million cycles. When we used a MIL-L-87177T lubricant, the first failure occurred at about 5 million cycles. Furthermore, the resistance of the failures was much different. Unlubricated connectors rather quickly developed resistances in the hundreds of kilohms. The contact resistance of lubricated connectors did not exceed 12 ohms until the onset of "end of life" failure when it went as high as 10 kilohms.

In some tests, we also applied a Commercial Lubricant. This lubricant was able to prevent the ultimate failure of one connector for more than 55 million cycles and another for more than 20 million cycles. In addition, this lubricant was able to restore the contact resistance of a severely degraded connector to a low and stable value. Six severely failed pins recovered immediately, and four more pins recovered after an additional 420 thousand cycles.

It is important to note that the susceptibility to fretting corrosion found in these tests does not necessarily equate to field failures. The vibration environment must cause sufficient micromotion between mated contact surfaces for fretting corrosion to occur, and the atmospheric constituents for corrosion must be present. Either measuring this amount of motion in situ or predicting it analytically is something we have yet to attempt. We do have the recent experience of an assembly including 66 of these Nano-miniature Connectors, unlubricated, which flew in a missile test in the spring of 1999. All data associated with that test was successfully transmitted and recovered. Thus, despite the apparent sensitivity of this connector series to fretting corrosion, a considerable number of them did work together throughout the test flight without functional failure.

At this point, it is our recommendation that it is unnecessarily risky to use a connector susceptible to fretting corrosion, and that a connector lubricant should be used to lessen that risk.

THE EXPERIMENT

Laboratory fretting tests were run on two different miniature connector configurations. One has a flat, rectangular shape with 51 contacts in two rows. The other is circular with 44 contacts. The contacts are the same in both configurations, a pin and socket pair made of BeCu and plated with a nominal 30 microinches of gold over 5 to 15 microinches of nickel. The socket has a small dimple near its entrance that forces the pin against the socket wall.

The connectors were mounted in a computer controlled fretting machine, specifically designed to test production hardware. This machine uses a Terfenol-D magnetostrictive transducer to produce fretting motion. After the connector was carefully inserted and aligned into the fretting machine, the contact resistance of each pin was checked. This procedure was necessary to insure that each pin was making good electrical contact. Then fretting motion was begun at a frequency of 30 Hertz and a displacement amplitude of 50 microns. A Keithley Four Wire Scanner was used to switch a HP 4338A Milliohmeter through all of the connector pins. This instrument limits current through the contact being measured to no more than 10 milliamperes and voltage across the contact to no more than 20 millivolts at 1000 Hz. Other than this measurement current, the contacts were run without electrical load throughout the test. The computer started the collection of contact resistance at channel 1 of the scanner, then switched the scanner through the rest of the connector pins. This process continued either until the resistance of five pins had exceeded our chosen 0.5 ohm failure level simultaneously on the same measurement cycle or until the test was stopped manually. The average initial resistance for the connector contact and the attached leads was approximately 0.28 ohm.

Twelve connectors were tested during this research project. Rectangular connectors were used during the first five tests. Circular connectors were used for the last seven tests. The connectors were tested under different conditions of lubrication. The test conditions and results are summarized in Table 1. Note that the connectors in Tests C2, D, E1, E2, G and J were treated with MIL-L-87177 lubricant. The lubricant was applied to the socket side of these connector pairs using a very thin artist's paintbrush. The connectors in Tests H, and K were also treated with MIL-L-87177 lubricant, but in these cases it was applied to the pin side by simply pouring lubricant into the connector and then pouring it back out. The connectors in Tests L and M were treated with the Commercial Lubricant. In Test L lubricant was brushed into the socket side. In Test M lubricant was poured into the pin side and then poured back out.

Other details of each test and representative data plots from several test runs will be explained in the following sections.

RESULTS

Table 1 - Summary of Test Conditions and Results

Test	# of pins	Lubricant	Lubricant Application Technique	Cycles to first failure > 0.5 ohm	Max # pins failed together	Max observed contact resistance	# cycles for max CR	Comments
A1	51	none	-	11,413	14	350 K ohms	10×10^6	Recovered to 0 failures after 421,170 additional cycles
A2	51	Comm. Lube	brush in socket	0	4	0.03 ohms		
B	51	none	-	40,997	8	680 K ohms	12×10^6	stopped at 15×10^6 cycles
C1	51	none	-	2341	29	>500 K ohms		stopped at 10×10^6 cycles
C2	51	MIL-L-87177	brush in socket	0	25	280K		C1 pins lubed & run 10^6 cycles
D	51	MIL-L-87177	brush in socket	1,775,024	6	<12 ohms	7×10^6	
E1	25	MIL-L-87177	brush in socket	3,015,873	1	0.6 ohms	3×10^6	Test E1 stopped at 15×10^6 cycles
E1	26	none	brush in socket	45,238	9	490 K ohms	13×10^6	
E2	25	MIL-L-87177	brush in socket	639	2	6 ohms		Test E1 pins (re)lubed and run 6×10^6 cycles
E2	26	MIL-L-87177	brush in socket	25	12	200 K ohms		
F	44	none	-	11,100	10	180 K ohms	280 K	stopped at 320K cycles
G	44	MIL-L-87177	brush in socket	430,097	5	<75 ohms	800 K	stopped at 800K cycles
H	44	MIL-L-87177	pour onto pins	-	0	-		No failures in 20×10^6 cycles
J	44	MIL + T	brush in socket	5.3×10^6	5	10 K ohms	7×10^6	stopped at 7.2×10^6 cycles
K	44	MIL + T	pour onto pins	$\sim 5 \times 10^6$	1	2.8 ohms	7.6×10^6	stopped at 22.5×10^6 cycles
L	44	Comm. Lube	brush in socket	$>55 \times 10^6$	5	>100K ohms	56×10^6	
M	44	Comm. Lube	pour onto pins	-	0	-	-	No failures in 20×10^6 cycles

Test A

Test A was run on a 51 pin, initially unlubricated, rectangular connector to characterize the fretting behavior of a new connector as it comes from the manufacturer. The first pin failure (contact resistance greater than 0.5 ohm) occurred at 11,413 fretting cycles. By 10 million fretting cycles 14 pins had failed, the maximum observed contact resistance was 350 kilohms, and the connector had been driven far into failure. The data for this portion of the test are summarized as A1 in Table 1. At this point after the unlubricated behavior had been well established, a recovery attempt was made using the Commercial Lubricant. The connector pair was separated, lubricated with Commercial Lubricant and reassembled. The number of failed contact pairs immediately dropped to 4, and they exhibited relatively low contact resistance values. Over the next 421 thousand cycles, all of the contact pairs recovered to less than 0.5 ohms. These data are summarized as A2 in Table 1.

The data for this test run are shown graphically in Appendix A. Figure A1 shows the maximum resistance of all of the failed pins (contact resistance greater than 0.5 ohm) throughout the test. Contact resistance peaked at near 350 kilohms at approximately 8 million cycles and again at the end of the 10 million cycle unlubricated test. Figure A2 shows the average resistance of all of the pins in failure as a function of the number of cycles. This way of viewing the data tends to diminish the effect of a high resistance outlier and to emphasize the behavior of the more typical failed contacts. Figure A3 shows the number of pins in failure throughout the test. The range of the black vertical line at any point on this graph indicates the number of contacts found to be in failure at adjacent readings. At the 10 million operation point, when the connector was separated, one contact pair was damaged and not measurable thereafter. This accounts for the one contact pair shown in failure in the later part of the lubricated test run.

In this test the Commercial Lubricant was able to restore all of the contacts, first driven into extreme fretting failure, to a low and stable contact resistance after 421,170 additional fretting cycles.

Test B

This test was run on a 51 pin, unlubricated, rectangular connector to further characterize the fretting behavior of a new connector as it comes from the manufacturer. The data for this test run are similar to Test A and are summarized in Table 1. The first detected contact resistance failure was at 40,997 fretting cycles. During the first 2.5 million fretting cycles the number of failed pins reached 6, but never went beyond 8 throughout the remainder of the 15 million fretting cycles. Contact resistance peaked at 680 kilohms at 12 million fretting cycles.

Test C

Test C is similar to Test A. A fresh 51 pin rectangular connector was fretted for 10 million cycles with first failure occurring at 2341 cycles, 29 contacts failing by the end of the first phase of the test, and contact resistance in excess of 500 kilohms being observed. The data for this portion of the test are similar to Test A and are summarized as C1 in Table 1. A recovery attempt was then made, this time by separating the connectors, brushing MIL-L-87177 lubricant into the socket contacts, and reassembling them. In the next one million cycles shown as C2 in Table 1, 15 to 25 pins remained in failure with peak contact resistance of approximately 280 kilohms.

This test demonstrated that the MIL-L-87177 lubricant is not able to recover all pins first driven into extreme fretting failure.

Test D

Test D was run with the MIL-L-87177 lubricant applied to a fresh 51 pin rectangular connector that had not been previously degraded. The first failure on the lubricated pins was recorded at 1,775,024 fretting cycles. Six pins failed by 13 million cycles when the test was terminated. In contrast to the previous tests on unlubricated connectors where failed contacts measured in the hundreds of thousands of ohms, the peak contact resistance observed on this test was less than 12 ohms.

Test E

This 51 pin rectangular connector was tested under two different conditions. The first condition will be referred to as Test E1 and the second as Test E2.

In Test E1, 25 of the pins in the connector were lubricated with MIL-L-87177, while no lubricant was applied to the other 26 pins. This provided an opportunity to compare the results of the lubricant within a single connector. The first failure on the lubricated pins was recorded at 3,015,873 fretting cycles. By 15 million cycles when this phase of the test was stopped, only one lubricated pin had "failed" and its contact resistance had not exceeded 0.6 ohms. In contrast, the first of the unlubricated pins failed at 45,238 cycles. By 15 million cycles, 9 unlubricated pins had failed, and the peak contact resistance observed was 490 kilohms.

For Test E2, the connector was separated, lubricated with MIL-L-87177, and reassembled. So the group of 25 pins were lubricated for a second time, and the group of 26 pins were lubricated for the first time. The first failure on the 25 relubricated pins happened at 639 fretting cycles after the test was restarted. For the 6 million additional cycles that Test

E2 ran, two of the twice lubricated pins failed, but neither pin exceeded 6 ohms contact resistance. The first failure on the 26 pins that were lubricated for the first time (recovery attempt) happened at 25 fretting cycles. During the next 6 million cycles, anywhere from 2 to 12 pins were in failure, and the peak observed contact resistance was approximately 200 kilohms.

Our observations from Tests D and E are that the MIL-87177 lubricant, if applied initially to the 51 pin rectangular connectors, is able to extend the initial onset of failure from the 2,000 to 45,000 range to well above 1 million cycles, and that the resistance level of "failed" lubricated contacts is well under 12 ohms, nearly five orders of magnitude less than that observed on unlubricated contacts. We also observe that the MIL-L-87177 lubricant is not able to "recover" pins previously driven into extreme fretting failure, as the Commercial Lubricant was able to do after some 400 thousand additional fretting cycles in Test A.

Test F

In tests F and beyond, 44 pin circular connectors were used. This test was run on a factory-fresh connector without lubrication. The first failure was observed at 11,100 cycles. Eleven contacts had failed by 320K cycles when the test was stopped. Contact resistance peaked at 180 kilohms and 280 thousand fretting cycles.

Behavior of this unlubricated circular connector does not seem to be substantially different from the unlubricated rectangular connectors of tests A, B, C and E.

Test G

Test G was similar to Test D, but using a 44 pin circular connector. MIL-L-87177 lubricant was applied by brushing it into the socket side of the connector. The first failure on the lubricated pins was recorded at 430,097 fretting cycles. By eight hundred thousand cycles when the test was stopped, 5 pins had failed. The peak contact resistance observed was less than 75 ohms.

Test H

Test H was a repeat of Test G. A factory-fresh, 44 pin circular connector was treated initially with MIL-L-87177 lubricant, but the lubricant was applied by pouring it onto the pin side of the connector and then pouring it out. The test was terminated at 20 million cycles, and no pins had failed during the entire test.

Test J

Test J was also run on a 44 pin circular connector. In this case, MIL-L-87177T lubricant was ued. Lubricant was applied by brushing it into the socket side of the connector. The first failure occurred at 5.3 million cycles. By 5.8 million cycles, a second contact had started to fail, and contact resistance was beginning to climb rapidly. Contact resistance hit a maximum value of 10 kilohms at 7 million cycles. The test was stopped at 7.2 million cycles. In comparison with Test G which used the same lubricant application method but the unmodified MIL-L-87177 material, failure on this test did not occur until an order of magnitude number of cycles later.

Test K

Test K was run on a 44 pin round connector with MIL-L-87177T lubricant poured into the pin side and then poured out. This test ran to approximately 5 million cycles before the first failure occurred. Only one pin failed throughout the 22.5 million cycles of the test, and its peak contact resistance was 2.8 ohms and occurred at 7.6 million cycles.

Test L

Test L was run with the Commercial Lubricant applied by brushing into the socket side of the connector. It ran without failure for 55 million operations. By 56 million operations, 5 pins were in failure with maximum contact resistance exceeding 100K ohms.

Test M

Test M was run with the Commercial Lubricant poured into the pin side of the connector and then poured out. This test was terminated at 20 million cycles. No failures were observed.

INTERPRETATION

It is quite apparent that this particular series of connectors, without a lubricant, is quite prone to fretting corrosion. In five tests, A1, B, C1, E1 and F, the first failure occurred in a range from 2341 to 45, 238 cycles. Further, the contact resistance measured in these tests increased to hundreds of thousands of ohms. For those who wonder what the contacts might do if they were fretted "dry" and then measured at higher voltage, we can report that previous tests on other, less susceptible gold versus gold connectors have demonstrated that as much as 24 volts applied to the contact through a 10 ohm series resistor does not consistently recover a failed contact to a low and stable resistance. From these test results and our previous experience, it is reasonable to conclude that an application in which these connectors were subjected to vibration sufficient to cause fretting corrosion would be very likely to fail early in its life due to noisey and high resistance connector contacts.

MIL-L-87177 Lubricant

When unmodified MIL-L-87177 Lubricant is applied to the connectors before any fretting occurs, as in tests D, E1, G and H, much different behavior is observed. The first instance of a contact exceeding 0.5 ohm is pushed back to the range from 430,097 to greater than 20 million cycles. Moreover, the contact resistance of lubricated pins in failure (except for Test G at the very end of its range which hit 75 ohms and test J at the end of its range which hit 10 kilohms) did not exceed 12 ohms, in contrast to the hundreds of thousands of ohms seen in unlubricated contacts. Clearly, unmodified MIL-L-87177 lubricant improves the fretting performance of these connectors.

Well into this experiment, when Test G had shown that the first failure in a lubricated 44 pin circular connector had occurred at 430,097 cycles in contrast to the range for first failure in the 51 pin rectangular connectors of from 1,775,024 Test D) to 3.015, 873 (Test E1), and when the Test G connector had gone to 75 ohms at 800,000 cycles in contrast to the others staying under 12 ohms for at least 10 million cycles, we our MIL-L-87177 lubricant supplier to see if there might be some improvement available in the lubricant. In response, he provided us with the lubricant plus an additive, MIL-L-87177T, described in footnote 2. We ran two connectors with this material (Tests J and K), with the result that first failures were observed at about 5 million cycles. Further, no effect was seen on initial contact resistance. The only MIL-L-87177 lubricant run that exceeded those results was that of Test H, in which no failure was detected up to 20 million cycles when the test was stopped. MIL-L-87177T lubricant may provide better protection against fretting corrosion, but more work needs to be done to separate the effect of the additive from the effect of the application technique.

The later tests in the sequence, H, K, L and M, were conducted by pouring the lubricant into the pin side of a circular connector and then pouring it out, as opposed to painting it into the socket side with a brush as was done in the earlier tests. H, run with straight MIL-L-87177, and and K run with MIL-L-87177T lubricant, were two of the best runs in terms of cycles to failure and maximum observed resistance. It is also possible that pouring the lubricant onto the pins and allowing it to thoroughly wet them is superior to painting it into the sockets. There may be a better and more practical method of applying the lubricant, perhaps to both sides of the interconnection, that would yield still better results. More work needs to be done in this area.

Commercial Lubricant

In Tests A2, L and M of this series, the connectors were treated with the Commercial Lubricant.

In test A2, we demonstrated that the Commercial Lubricant actually recovered an unlubricated connector that was fretted for 10 million cycles and driven deeply into failure. Six severely failed pins recovered to less than 0.5 ohms immediately, and four more pins recovered during the next 420 thousand fretting cycles. After recovery, this connector maintained low and stable contact resistance values for an additional 10 million fretting cycles. By contrast in test C2, MIL-L-87177 was not able to recover contacts similarly damaged by fretting.

In Test L, the Commercial Lubricant was able to provide protection against fretting corrosion for more than 55 million cycles. And in Test M, it was able to provide protection for the 20 million cycles that the test was run before it was

APPENDIX A

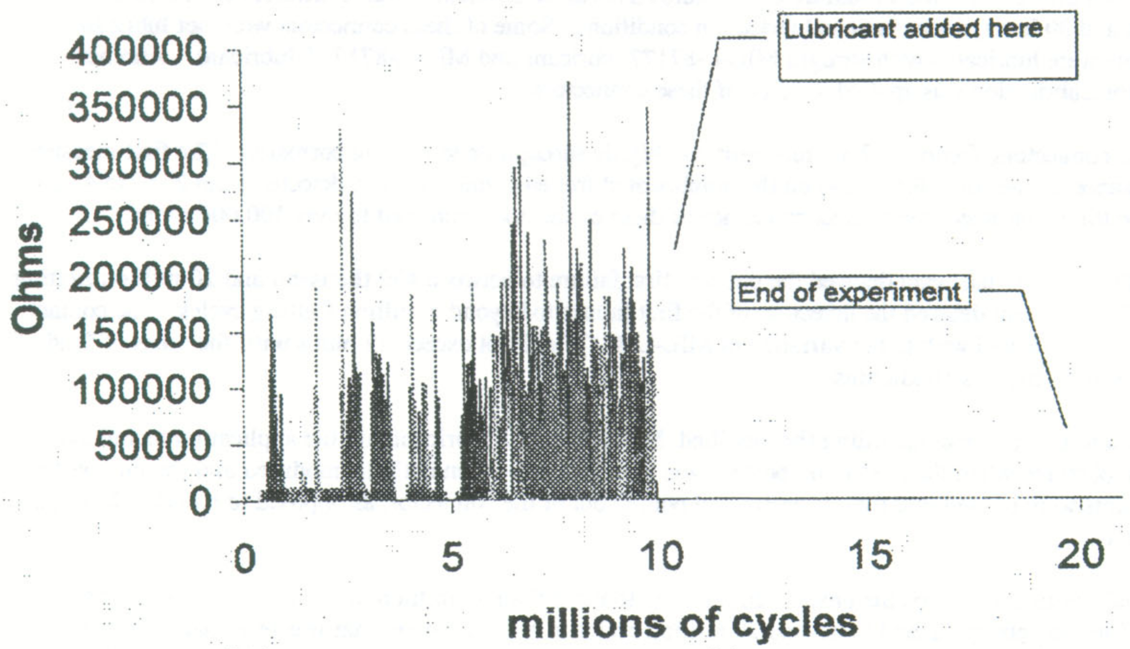

Figure A1. Maximum resistance of all failed pins (resistance > 0.5 ohm) throughout Test A. The Commercial Lubricant was added at 10 million cycles.

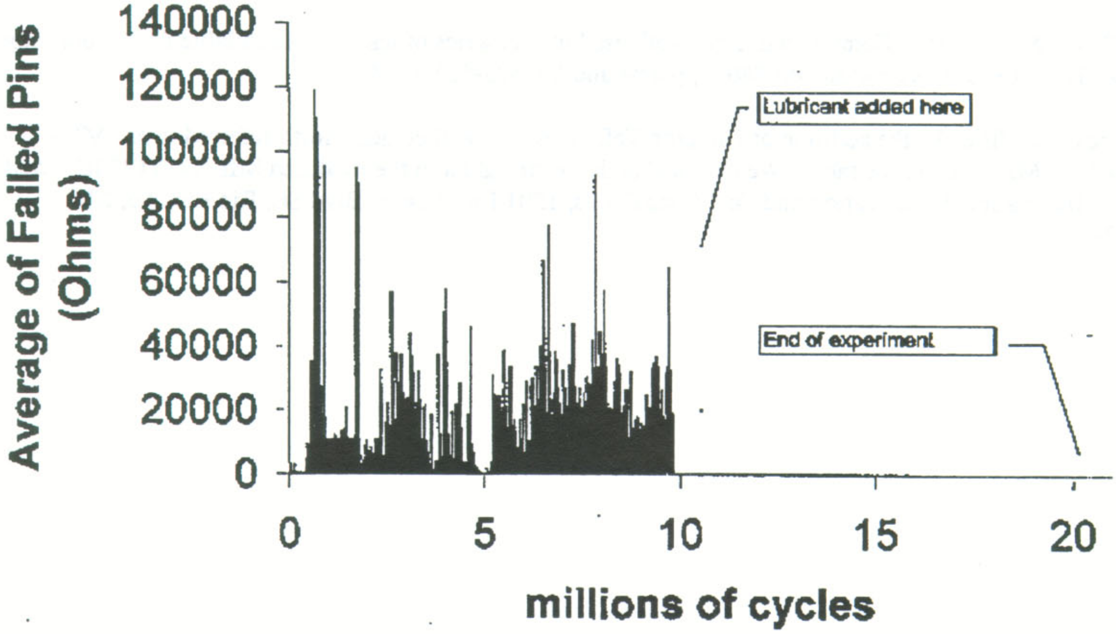

Figure A2. Average resistance of all failed pins (resistance > 0.5 ohm) throughout Test A. The Commercial Lubricant was added at 10 million cycles.

stopped. Judging from these test results on the criterion of preventing fretting corrosion alone, the Commercial Lubricant appears to be superior to MIL-L-87177 material.

CONCLUSIONS

A fretting research project on Nano-miniature Connectors has been completed. Twelve different connectors were fretted at 50 microns and 30 hertz, under various lubrication conditions. Some of these connectors were not lubricated, while other connectors were lubricated with straight MIL-L-87177 lubricant and MIL-L-87177T lubricant. Another Commercial connector Lubrication was applied to some of these connectors.

Nano-miniature connectors, fretted without lubricant, are highly susceptible to fretting corrosion. The first measured failure (contact resistance greater than 0.5 ohms) on the unlubricated fretted connectors was detected from 2341 to 45,238 fretting cycles. As fretting continued, the contact resistance of these connectors increased to over 100,000 ohms.

Unmodified MIL-L-87177 lubricant delayed the onset of first failure to between 430 thousand and 20 million fretting cycles. MIL-L-87177T lubricant delayed the detection of the first failure to beyond 5 million fretting cycles. The contact resistance of connectors lubricated with either variation of MIL-L-87177 did not exceed 12 ohms until the onset of "end of life" failure when it went as high as 10 kilohms.

There is confounding in the data regarding the modified, MIL-L-87177T lubricant and the application technique. The best results were obtained when the modifying powder was used and also when both the modified and the unmodified MIL-L-87177 lubricants were poured into the connector and poured out of the connector, as opposed to its being brushed into the socket contacts.

The Commercial Lubricant delayed the onset of first failure to more than 55 million cycles in one test that was conducted until a failure was observed, and to beyond 20 million cycles in an experiment that was terminated before detecting a failure. The Commercial Lubricant actually recovered an unlubricated connector that was fretted for 10 million cycles and driven deeply into failure. Six severely failed pins recovered to less than 0.5 ohms immediately, and four more pins recovered during the next 420 thousand fretting cycles. After recovery, this connector maintained low and stable contact resistance values for an additional 10 million fretting cycles. MIL-L-87177 lubricant was not able to recover a connector under similar conditions.

1 – CLT: X-10 is the Trade Name of the "Commercial Lubricant" used in this series of tests. It is available from Connector Lubricant Technology, 1755 Royal, Las Cruces, NM 88011, phone and fax 505-522-1518.

2 – MIL-L-87177 lubricant modified by the addition of 1 micron Teflon powder will be henceforth referred to as "MIL-L-87177T" in the text and as "MIL + T" in the table. We obtained both the straight and the modified MIL-L-87177 lubricant from George Kitchen at International Lubrication and Fuel Consultants, 1201 Rio Rancho Blvd SE, Rio Rancho, NM 87124, phone 505-892-1666.

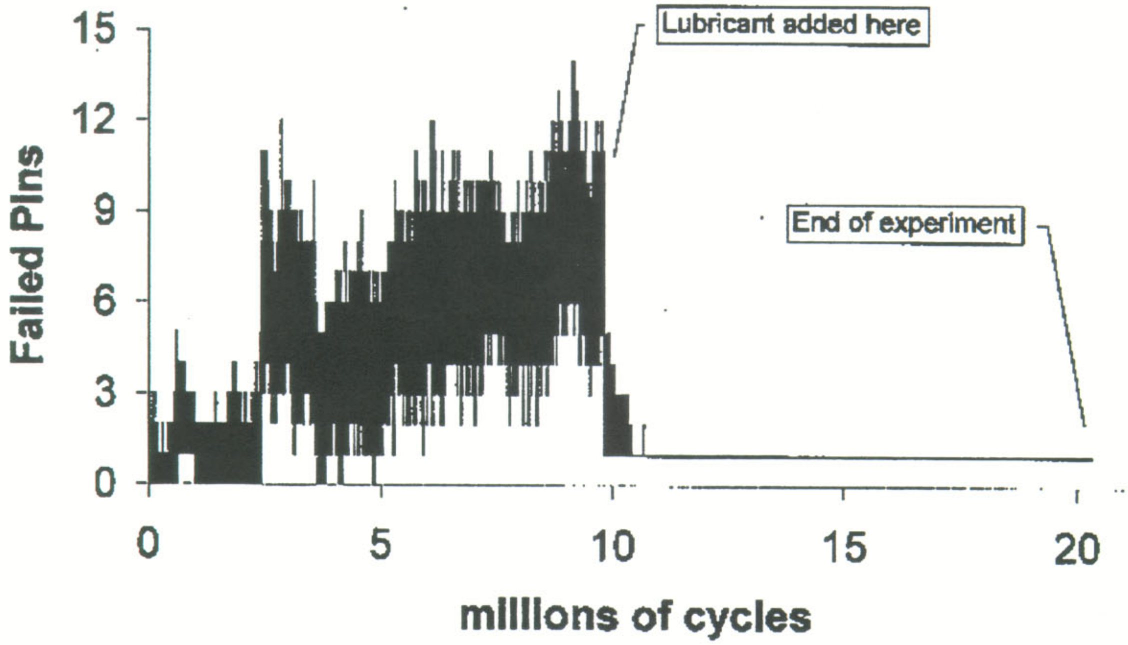

Figure A3. Number of pins in failure throughout Test A.

Appendix H

W. H. Abbott, "Final Report: Evaluation of Lubricants for Corrosion Inhibition on Electrical Connectors,"
(25 pages)

Battelle
. . . Putting Technology To Work
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December 3, 1998

Mr. James Hanlon
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-0523

Dear Mr. Hanlon:

Contract No. BD-0422/BD-0451

Final Report
Evaluation of Lubricants for
Corrosion Inhibition on Electrical Connectors

This letter is a final report on the subject project(s), which have been conducted for Sandia. Two closely related projects were conducted under separate contracts. Therefore, due to this close relationship, the results have been combined into this single report.

Background

Much of the background for this work is based on studies conducted for the Air Force and for which both a final report and a technical paper have been issued[1]. Sandia has copies of both documents. The earlier studies dealt with the subject of the corrosion inhibition of connector surfaces by the use of lubricants conforming to MIL-L-87177A and MIL-C-81309E.

The earlier work was very positive and identified several commercial, off-the-shelf (COTS) materials that offered both the potential for excellent corrosion inhibition and no adverse effects at an electrical interface. These conclusions were reached for both laboratory and field studies conducted under severe environmental conditions.

The earlier work was considered sufficiently positive that Sandia has expressed an interest in carrying this work further for possible use in DOE applications. Specifically, lubricants have

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[1] Abbott, W. H., "Field and Laboratory Studies of Corrosion Inhibiting Lubricants for Gold-Plated Connectors", *Electrical Contacts*, p 414 (1996).

been identified, but there are a number of open questions relating to the use of these lubricants in a manufacturing operation. These questions relate to (1) the effects of volatile carriers/solvents as must be used to apply the lubricant, and (2) the effects of lubricant concentration.

As indicated, the earlier work involved the application of lubricants as COTS materials, which have been available in aerosol/spray form. This means that the lubricant concentration left on the surface was largely unknown, possibly variable, and possibly far in excess of the minimum actually needed. For these reasons, an objective of the present work has been to repeat some portions of the earlier studies but in a much more controlled manner.

Objectives

The main objectives of these studies have been twofold. The first has been to address the issue of whether the nature of the volatile lubricant carrier has any effect on corrosion inhibition/contact performance. This is not an issue that has been addressed in previous published studies and there is little basis for predicting whether any effect should exist. However, it is an important technical issue not only for contact performance but also to have available several carrier options to address any materials compatibility or environmental issues.

The second objective has been to evaluate the effects of the concentration of active lubricant in a volatile carrier. This is also important for use in any manufacturing operations in which lubricant can be applied in a more controlled manner than in the field. Typically, a desirable practice would typically be to use the minimum amount of lubricant necessary to achieve the desired objective, which in this case is corrosion inhibition.

Research Studies

Overview

The experimental details were identical in every respect to those given in the two references cited earlier. In fact, extra hardware from the earlier studies were immediately available to this program such that the present studies should have duplicated earlier procedures in nearly every respect.

In this work, the test vehicle was a gold-gold-edge card connector. The gold plating on both halves was 30 microinches of acid hard gold over 50 microinches of nickel over copper (simulated pc boards) or phosphor bronze (connector springs). The latter approached a zero porosity condition; however, the pc boards had a very high porosity level.

The study was simple in concept. It was known that due to the high porosity level on the pc board this was an excellent test vehicle for the purposes of this work. Lubricant was applied in a controlled manner to the pc board. It was then exposed to a corrosive gas environment in an unmated condition, periodically mated to a dedicated connector, and contact resistance was measured as the primary indicator of performance/corrosion inhibition. From earlier work, it was known that this test vehicle without lubrication would be degraded in a matter of a few days.

Lubricant

Only one lubricant is being used in this study at the request of Sandia. This is an 87177A material. We are aware that there are two commercial vendors for such a lubricant. From earlier work conducted for the Air Force, we are of the opinion that the performance of materials from both vendors are about the same. Therefore, we are of the opinion that either could have been used in this work with equivalent findings.

At the start of this program, the appropriate material was available from only one vendor. This was Lektro-Tech. The form of the material that was available was specifically identified as Lektro-Tech B, Super-Corr for Brush Application. This is a sufficient and unique identifier and means that the "lubricant" was supplied as a bulk liquid and not the aerosol version.

The product information sheets that accompanied the product indicated that the bulk liquid consisted of about 95-96 weight percent of a volatile carrier (HCFC141b) with the remainder being the active ingredients. This definition is important to note, since future references to lubricant concentrations will always refer to a weight percentage of the **bulk liquid** in various carriers. This means that in all cases the actual percentage of the active lubricant will be far lower than the reported percentage of lubricant.

Volatile Carriers

Our original proposal to Sandia listed three carriers to be studied with a single concentration of lubricant at five weight percent (as defined above). The three carriers were (1) HCFC 141b, (2) petroleum ether, and (3) HFE7100.

All of these were, in fact, prepared for study. However, it was quickly discovered that one of these "high-tech" solvents was very questionable as a solvent for this lubricant. For this reason, several other solvents were evaluated. These were (4) mineral spirits and (5) PF5080. It was also discovered that Item 5, which has frequently been used with other lubricants in work of this type, was questionable.

Table 1 summarizes the physical appearance of the lubricant formulations at five weight percent. The intuitive goal was to obtain formulations with total solubility as indicated by a clear liquid. Three such materials were eventually identified and studied to meet the minimum goals set forth in the SOW. However, since the other lubricants had been prepared, they were also included in the study for information.

Lubricant Deposition

All lubricants used in this work were applied by the common process of extraction from dilute solutions. This means that the part onto which a lubricant was to be applied was dipped into the five-percent solution, slowly withdrawn, and the volatile carrier allowed to evaporate. This single concentration of five percent was used only for this phase of the work.

The lubricant was applied to both sides of a gold-plated pc board. Although the following variables may not be critical, they were controlled as follows. The lubricant was at room temperature (24-25 C). The time in solution was about 15 seconds before the extraction was started. The extraction rate was "slow" and probably required about 15 seconds to pull a 3-inch length of pc board out of the solution. Each board was allowed to air dry for 24 hours at room temperature.

During the drying process, each board was contained in a small glass bottle with an open top. The orientation was about 60 degrees with only the ends of the pc boards touching the glass surfaces.

After about 24 hours, each sample was weighed on a microbalance (initial weights had been taken). The samples were further dried at 50 C and weighed after several intervals. The objective of these weighing operations was to document the amount of lubricant deposited on each sample.

A summary of these results is given in Table 2. These are experimental results, which are presented without any conclusions relative to performance.

Concentration Effects

As a result of the initial studies to be discussed shortly, a single carrier was defined as being particularly useful for this lubricant. This was HCFC 141b. This carrier served as the solvent for the second phase of the studies conducted under Contract BD-0451.

For this work, solutions were prepared and used exactly as described above but with four concentrations of lubricant. These were 3, 5, 10, and 20 weight percent. As always, a fifth "concentration" of zero/no lubricant was used for control purposes.

Independent test samples were prepared for each of these four conditions. These were treated and subsequently exposed in a Class-II environment in a manner identical to that discussed earlier.

Thermal Ageing

All of the studies described so far were on samples lubricated at room temperature and exposed near room temperature. It is recognized that there are many questions often raised in connection with the use of lubricants related to (1) long-term degradation, and (2) lubricant loss and the ability of the lubricant to give long-term protection. In order to address these issues, thermal ageing is usually employed.

An independent sample set was prepared that was identical to the four conditions described in the preceding section; i.e., 0, 5, 10, and 20 percent in HCFC 141b. These samples were aged in air at 80 C for 1,000 hours in a mated condition. After this ageing was completed, the boards were subjected to an unmated exposure in a Class-II environment in a manner identical to all other studies.

Corrosion Studies

The program plan was to expose the gold-plated samples to a Class-II FMG environment and periodically measure contact resistance as the measure of performance. In this work as in previous work, only the pc boards were exposed as an unmated connector exposure. After each interval, the boards were removed from the test chamber, mated to dedicated connectors, measured, unmated, and returned to the test chamber for further exposures. In addition to the lubricated samples, an unlubricated control was always used.

The sample size for each variable/lubricant was 100 contacts. Therefore, the statistics in this work should be relatively good. All measurements were at dry circuit conditions (50 mv, 10 ma).

The original program plan was to continue the exposures to about 20 days unmated or as required to demonstrate any differences among the various lubricant formulations. This was done even though it is recognized that such a lengthy unmated exposure is probably an extreme test for any system. More common unmated exposures in actual qualification programs are more on the order of 5 to 10 days.

Results

Carrier Effects

These results have been summarized in Figures 1 to 7 to show the nature of the data, the presentation format, and the actual results. All data are Delta R values taken on a pin-by-pin basis.

The results at 2 days show little degradation at this point. Also, it is significant to note no high readings, which could be indicative of problems associated with the lubricant. This is actually an expected result based on earlier work.

At 5 days, there was significant degradation as clearly shown for the unlubricated controls. Even at this point, it is clear that there is a significant difference among the various carrier formulations at the five-percent lube level. This is not a surprising result based on Table 1 and the discussion associated with it. Several formulations showed almost complete corrosion protection, and it is not surprising that the formulations with total solubility gave the best protection. However, the most surprising result was for the mixture containing petroleum ether. In spite of the fact that there appeared to be total solubility, the performance of this mixture was marginal at best.

Beyond 5 days of exposure, there was clear degradation on all samples. However, through at least 10 days, the HCFC 141b remained as the best choice of solvent.

These results served two important purposes. First, they defined a solvent to use for the next phase of the work. This was 141b. Second, they indicated that the five-percent concentration would probably not be sufficient to obtain the high degree of corrosion protection which was sought in this work. At the same time, it should again be noted that even the 5-day protection offered by this concentration would normally be considered "impressive" and probably adequate for many practical applications.

Concentration Effects

The results for the various lubricant concentrations in 141b are summarized in Figures 8 to 11. These data show a clear effect of concentration and a gradual loss of corrosion protection for some with exposure time. Only the 20-percent concentration was effective in providing complete corrosion protection through 20 days of exposure. This level of protection is considered somewhat remarkable for an unmated exposure compared with published results for most conventional contact lubricants.

Thermal Ageing

These results are summarized in Figures 12 to 16. Figure 12 is an accurate description of all data obtained throughout the thermal-ageing exposure. Measurements were actually made after 250,500 and 1,000 hours and both before and after interface "disturbance". In effect, these data show the very positive result that there was no indication of adverse lubricant degradation under any of these conditions.

Figures 13 to 16 show the results of the Class-II unmated exposures on the thermally aged samples. These results are very easy to summarize, since they are consistent with the earlier data regarding concentration effects. However, these data do provide a high degree of assurance that the lubricant will not suffer long-term degradation and will retain a high degree of corrosion inhibition even after long-term ageing.

Figure 16 does demonstrate that limits exist on the capability of any of these materials to inhibit corrosion. However, the extremes of both the thermal ageing and the unmated exposure necessary to degrade to 20-percent composition are probably far beyond what should ever be required for practical applications.

Conclusions and Recommendations

These studies have clearly defined at least one lubricant system of lubricant type, lubricant concentration, and volatile carrier, which appears to be capable of providing long-term corrosion protection even under environmental extremes. This is a 20-percent solution of an 87177A-type material in HCFC 141b.

A material of this type could be applied in a variety of ways. Therefore, the lubricant should be suitable for both field and manufacturing operations.

In view of these very positive results, we recommend that work of this type be extended to actual field exposures in a variety of environments to determine the full capabilities of the lubricant and to define any possible risks due to synergistic effects such as dust. We would also recommend that this work be extended to an evaluation of the tribological properties of such a formulation to include wear and fretting corrosion.

Finally, it should again be noted that these studies were conducted at relatively high levels of contact normal force (200 to 250 grams). It is recommended that similar work be conducted into the 50 to 100-gram regions in order to fully define the capabilities of these lubricants.

This completes our studies on these very interesting and important projects for Sandia. Please let me know if you have any questions on this report or if we can work with you further in this subject area.

Sincerely,

William H. Abbott
Project Manager
Advanced Manufacturing Technology

WHA:gw
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Table 1. Appearance of lubricant solution for five-percent lubricant with various carriers

Carrier	Appearance
Mineral spirits	Clear liquid
Petroleum ether	Clear liquid
HCFC 141b	Clear liquid
PF 5080	Limited solubility; oily liquid (probably lubricant) adhering to glass surfaces of container
PF 7100	Limited solubility; milky-white dispersion

Table 2. Residual lubricant on surface of gold coupon; application by dipping and extraction from solution

			Mass Loading, Micrograms/cm^2	
Sample I.D.	Carrier	Lube Concentration, weight percent	Initial 1 hour, 25 C	1 Hour, 50 C
101	Mineral spirits	5	27.5	30.9
102	Petroleum ether	5	24.1	33.5
103	PF 7100	5	23.1	33.5
104	PF 5080	5	135.7	122.0
105	HCFC141b	5	20.6	31.8

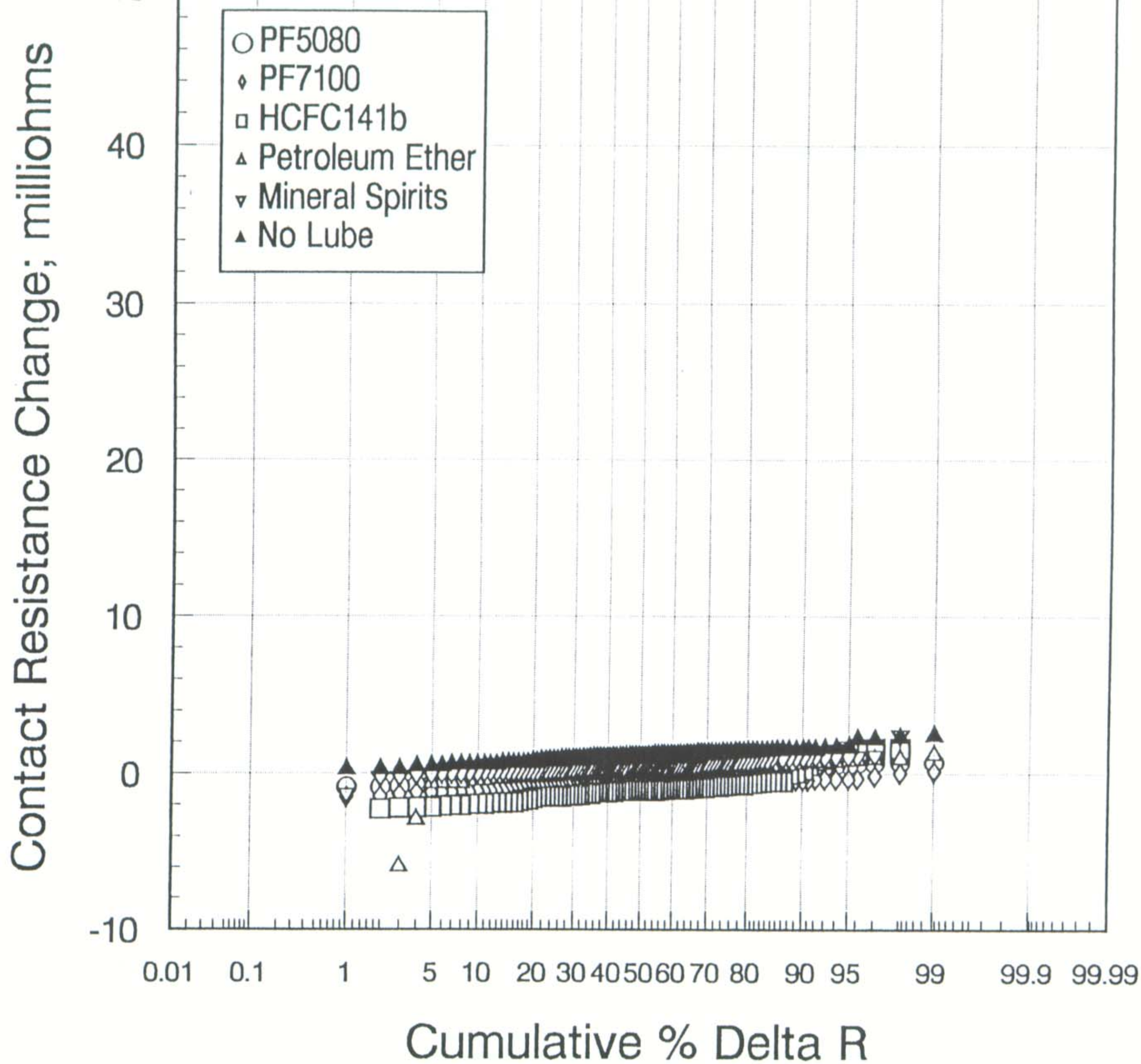

Figure 1. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 2 DAYS

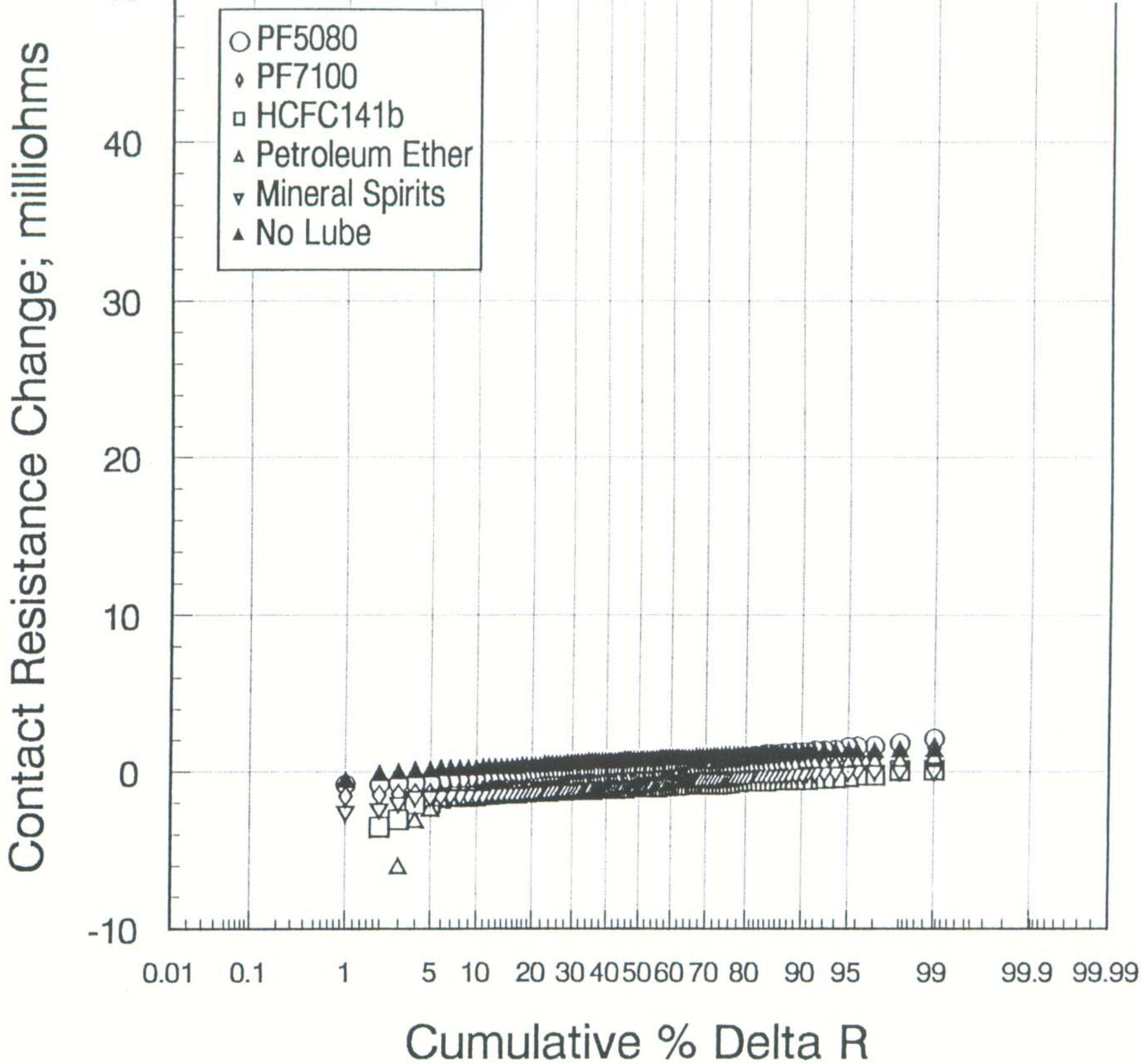

Figure 2. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 2 DAYS + CYCLE

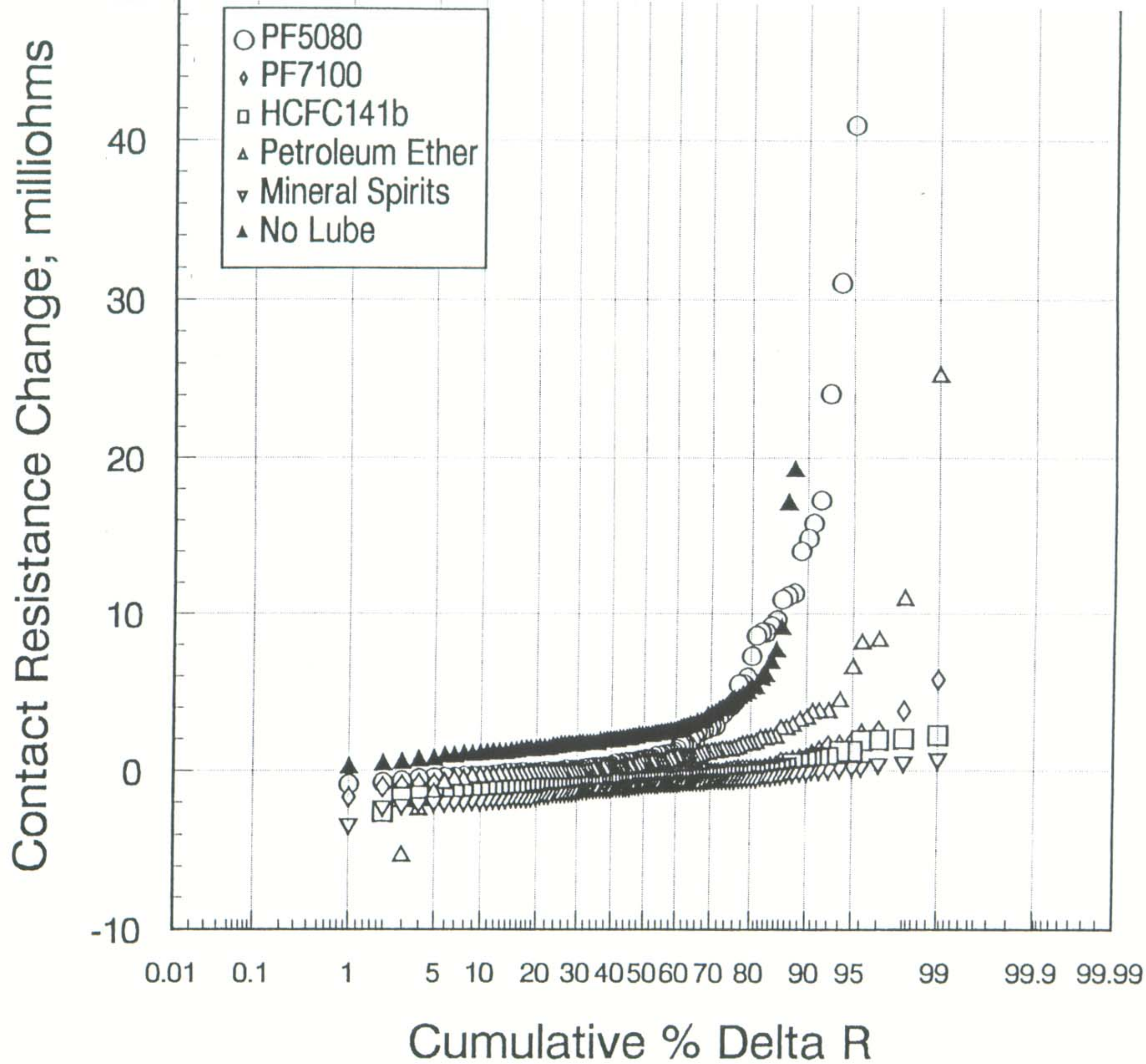

Figure 3. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 5 DAYS

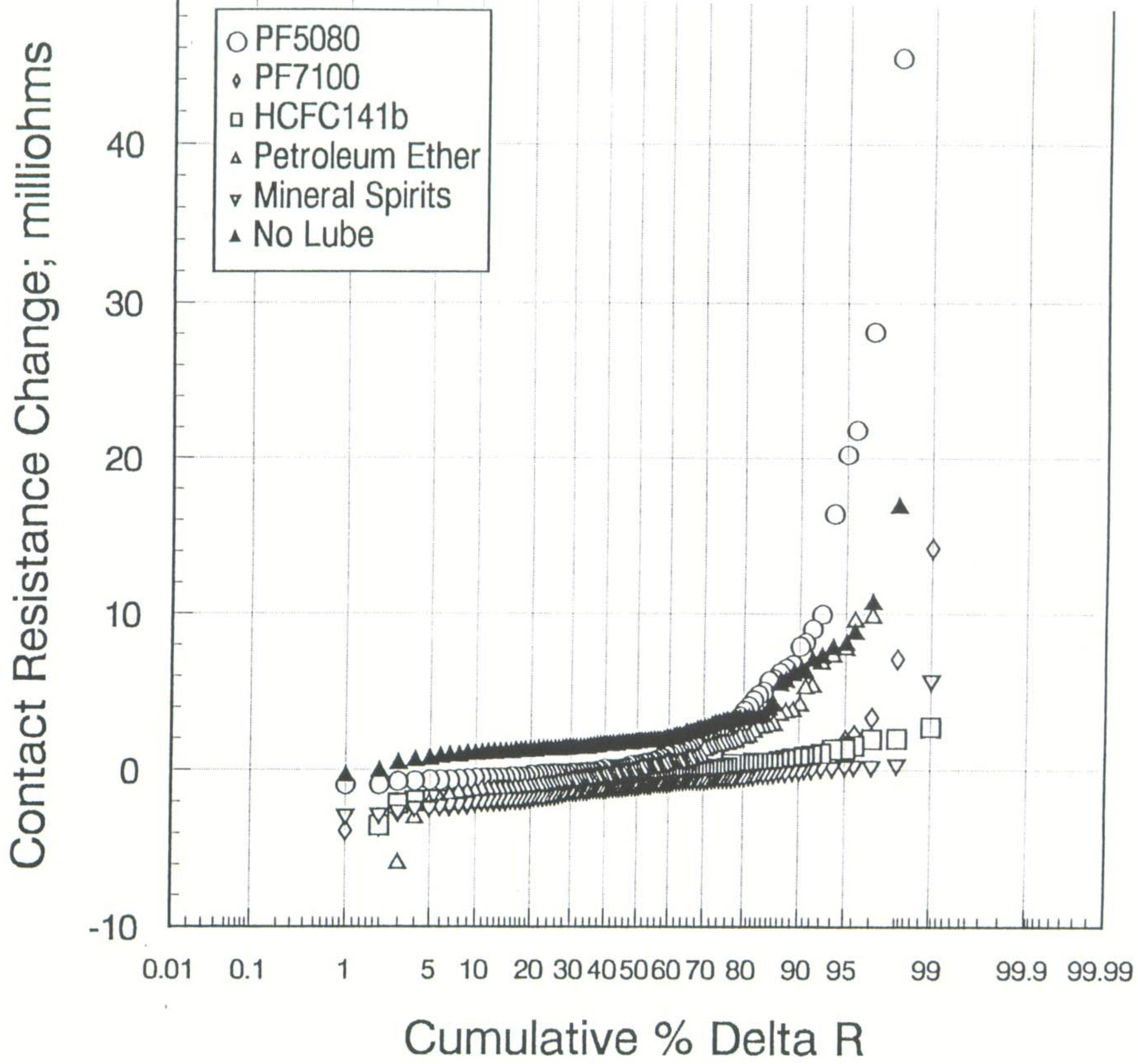

Figure 4. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 5 DAYS + CYCLE

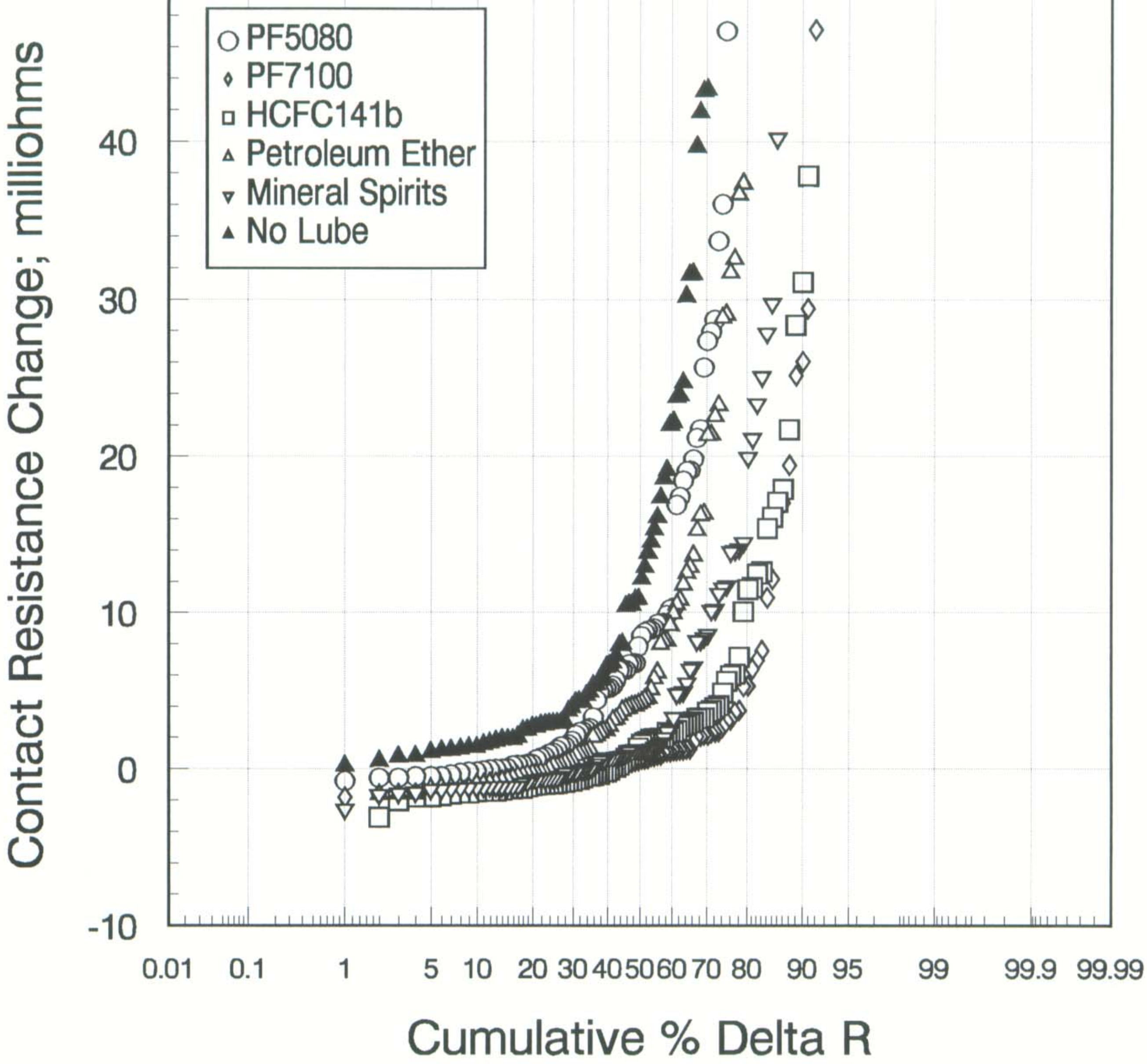

Figure 5. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 10 DAYS

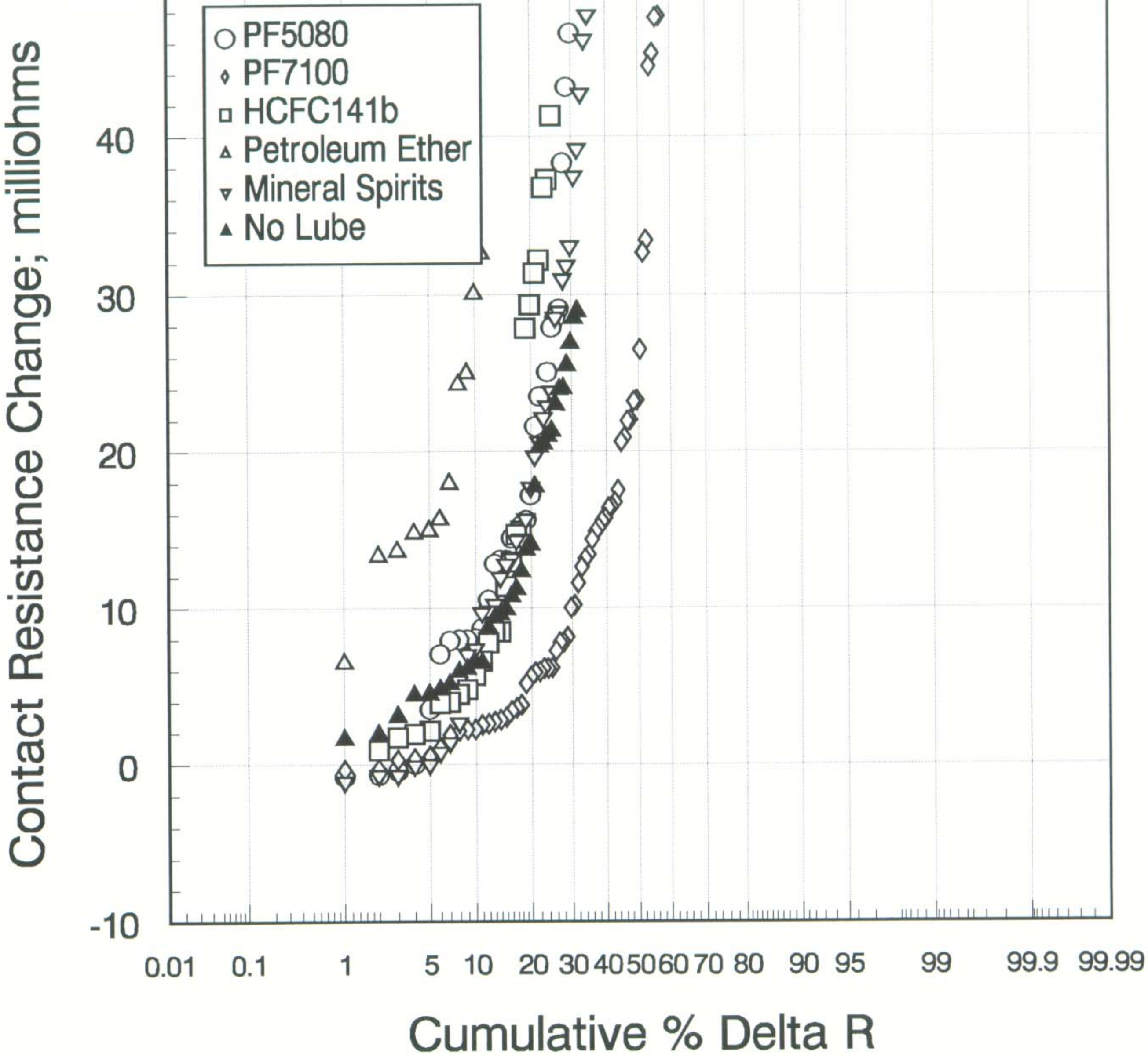

Figure 6. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 20 DAYS

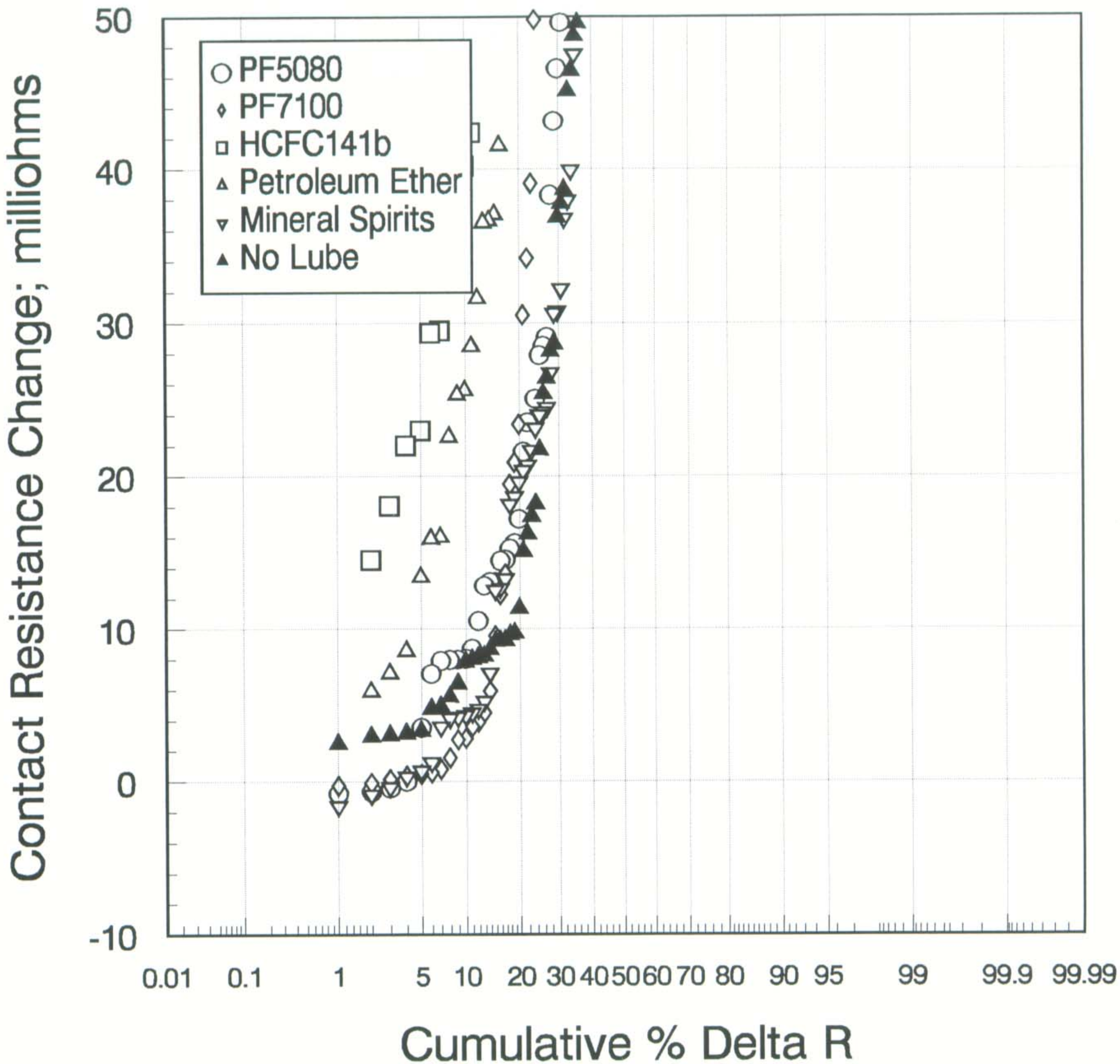

Figure 7. LUBRICANT CARRIER EFFECTS STUDY; 5 % L6; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 20 DAYS + 1 CYCLE

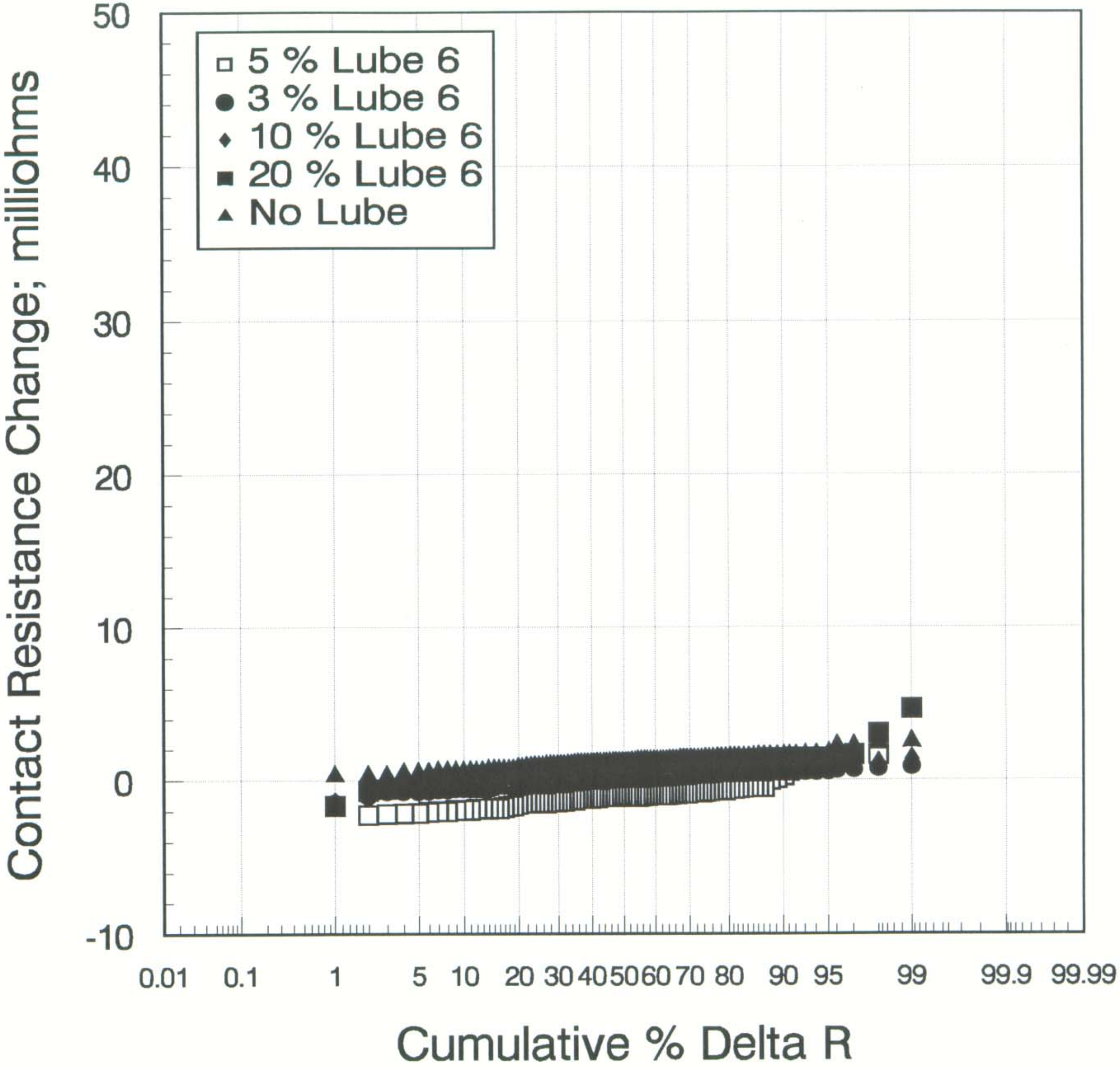

Figure 8. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 2 DAYS

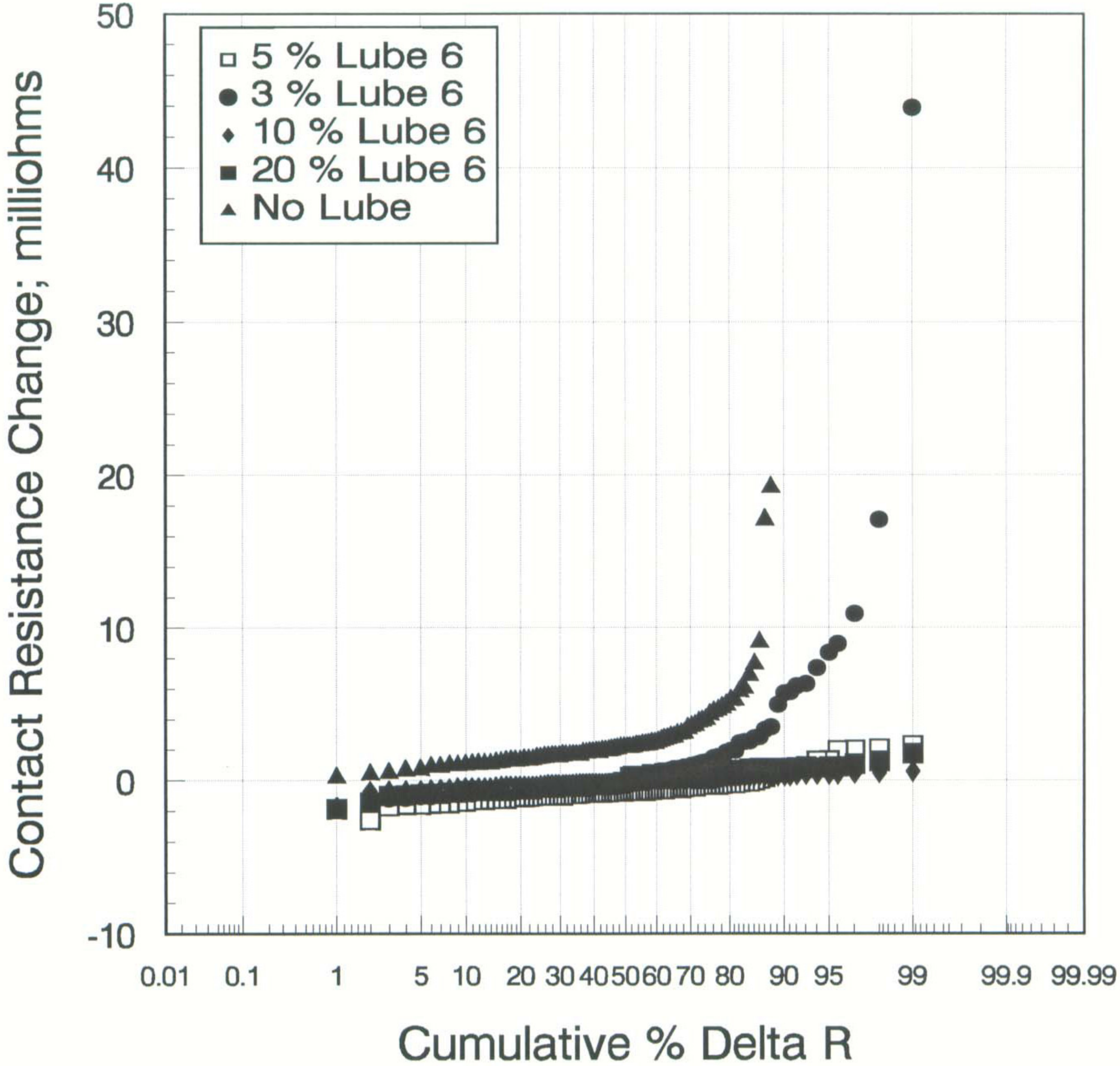

Figure 9. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 5 DAYS

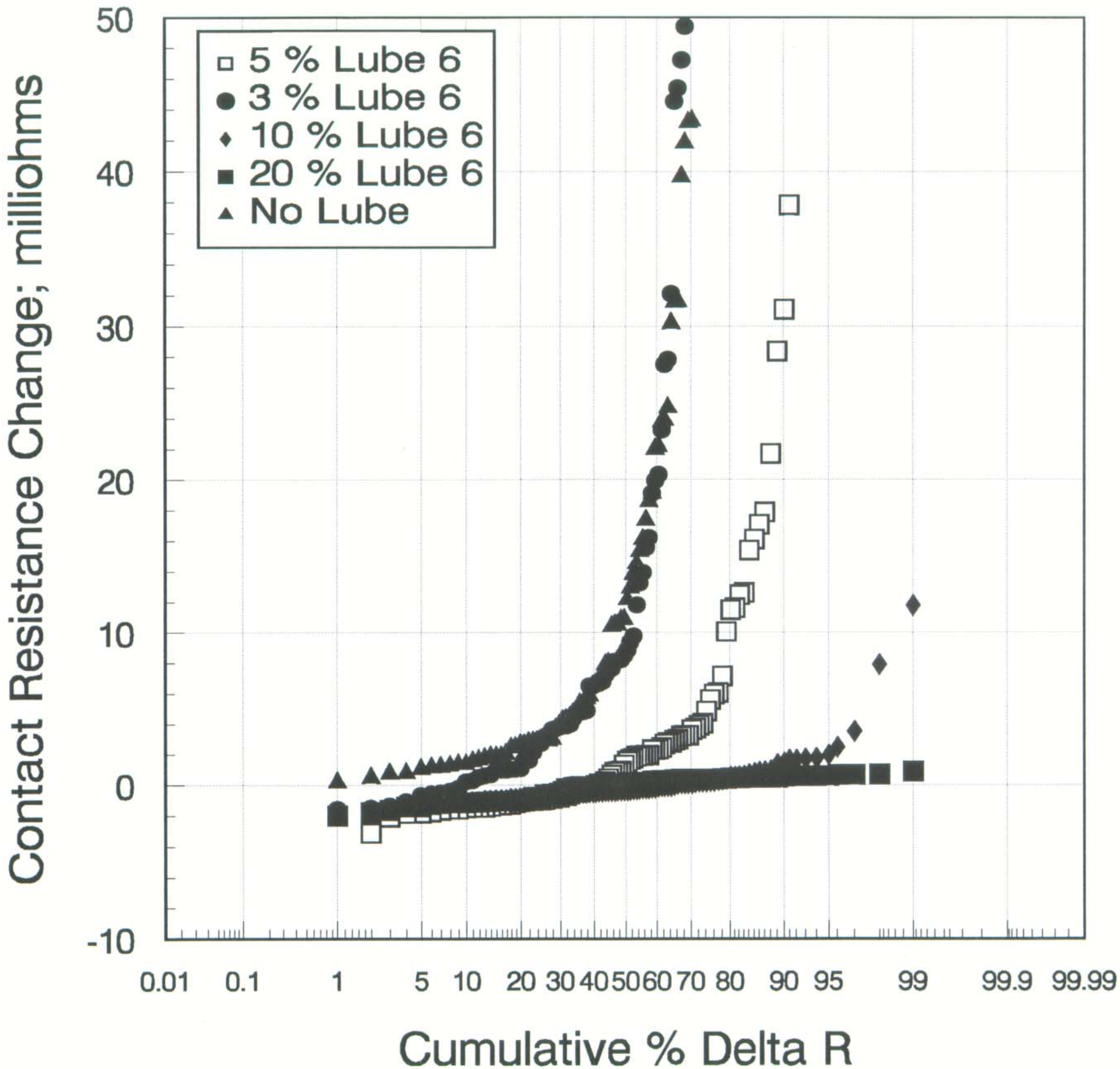

Figure 10. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 10 DAYS

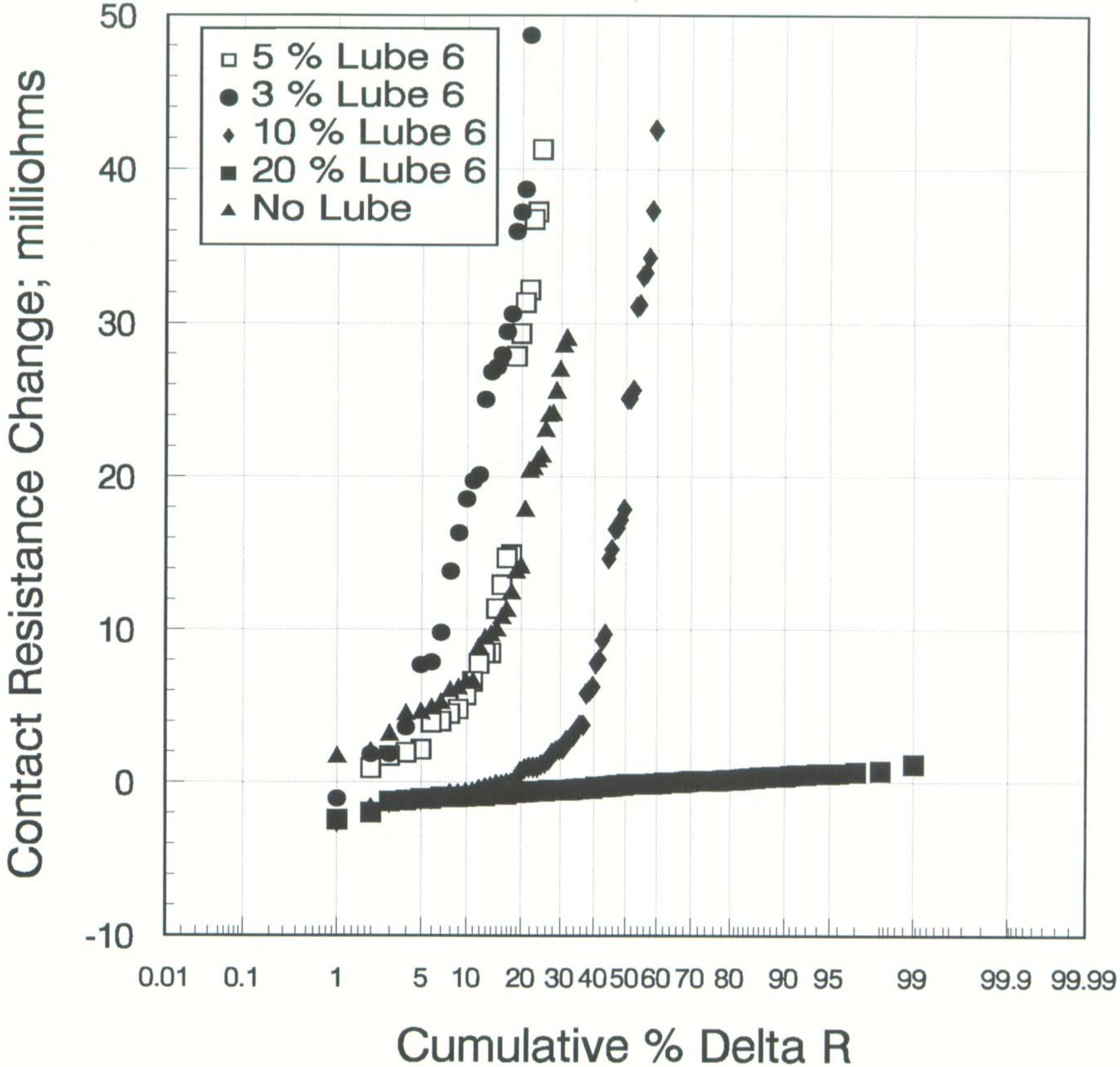

Figure 11. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 20 DAYS

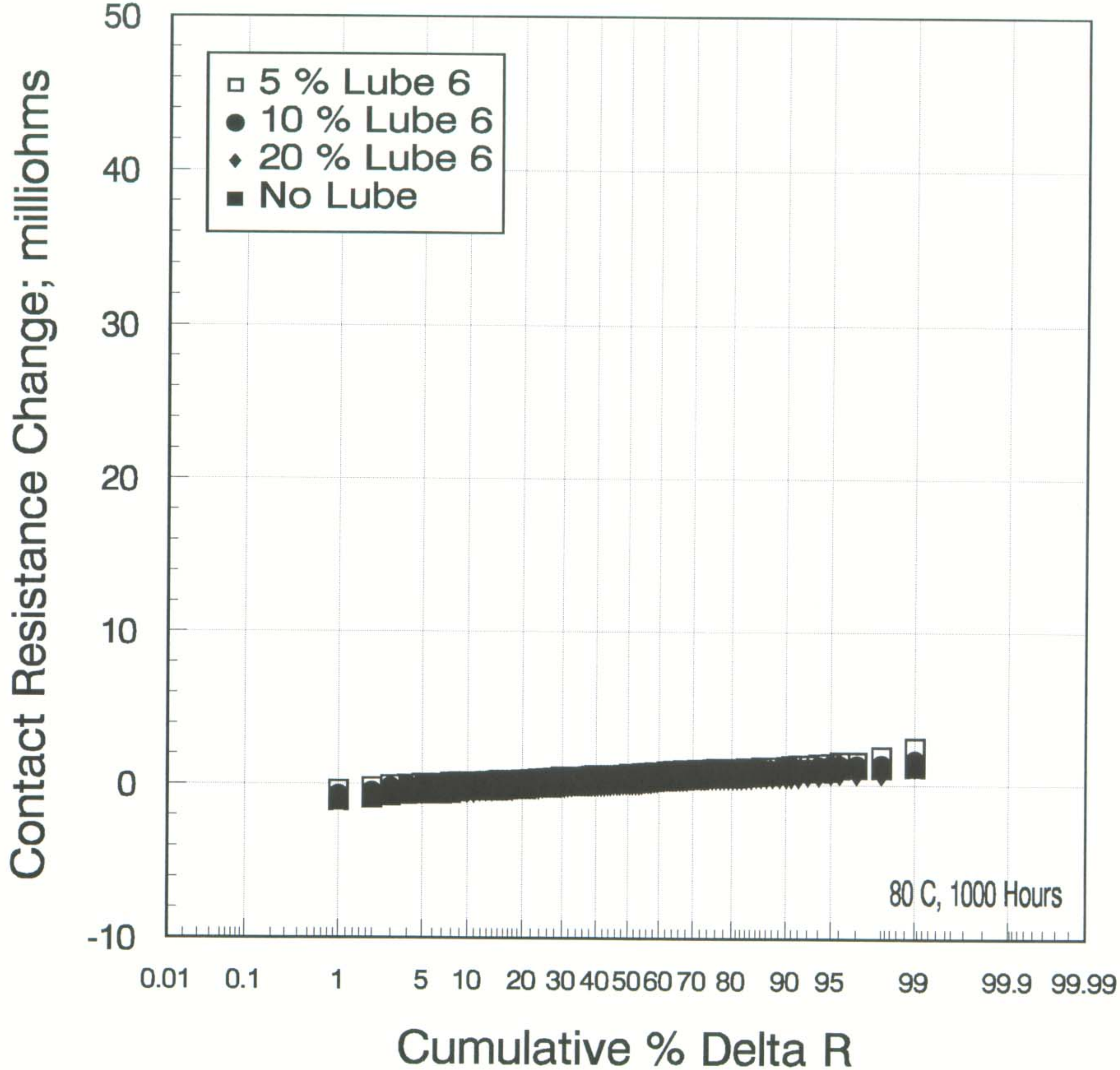

Figure 12. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 80 C THERMAL AGE

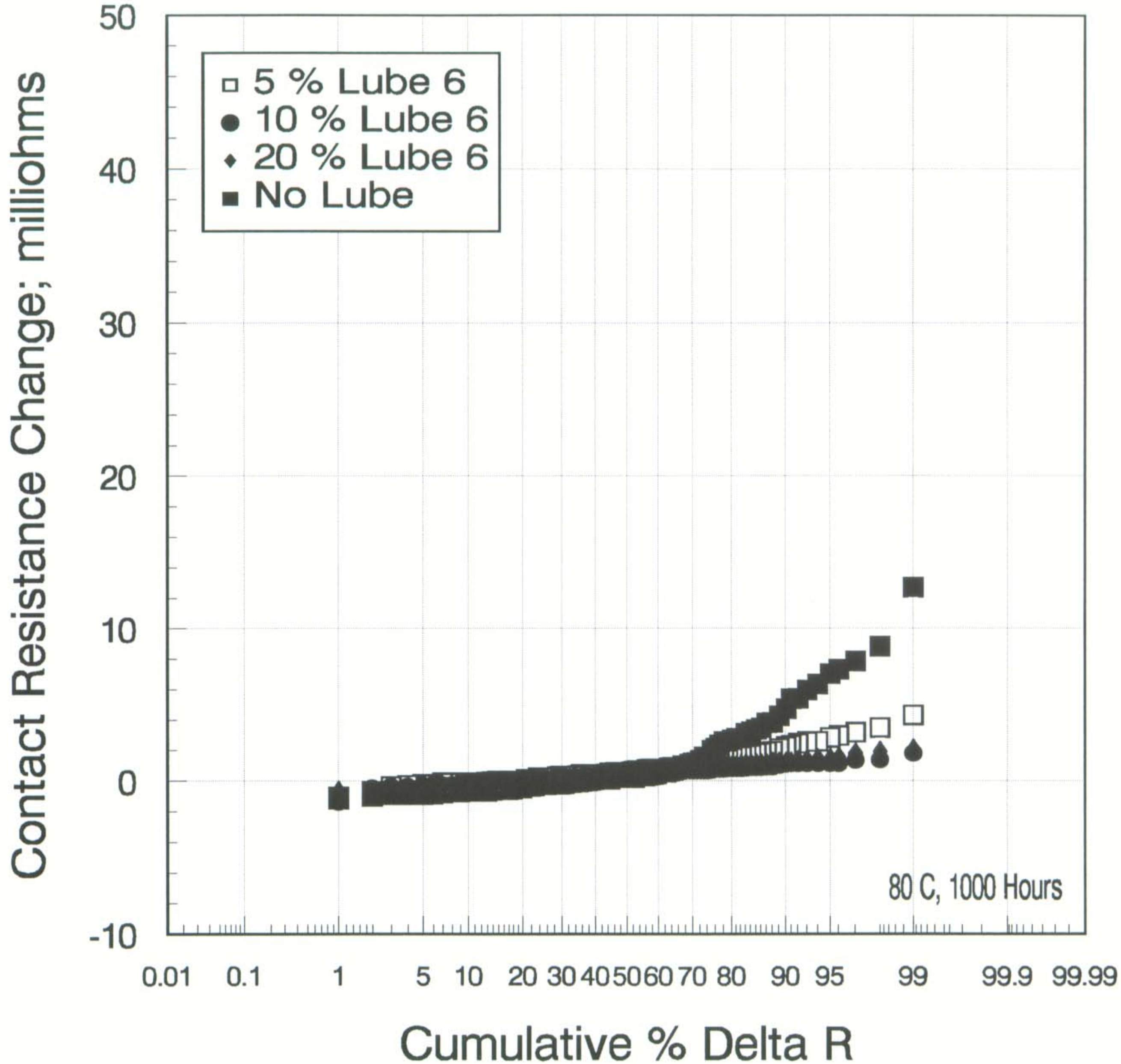

Figure 13. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 80 C THERMAL AGE + 2 DAY

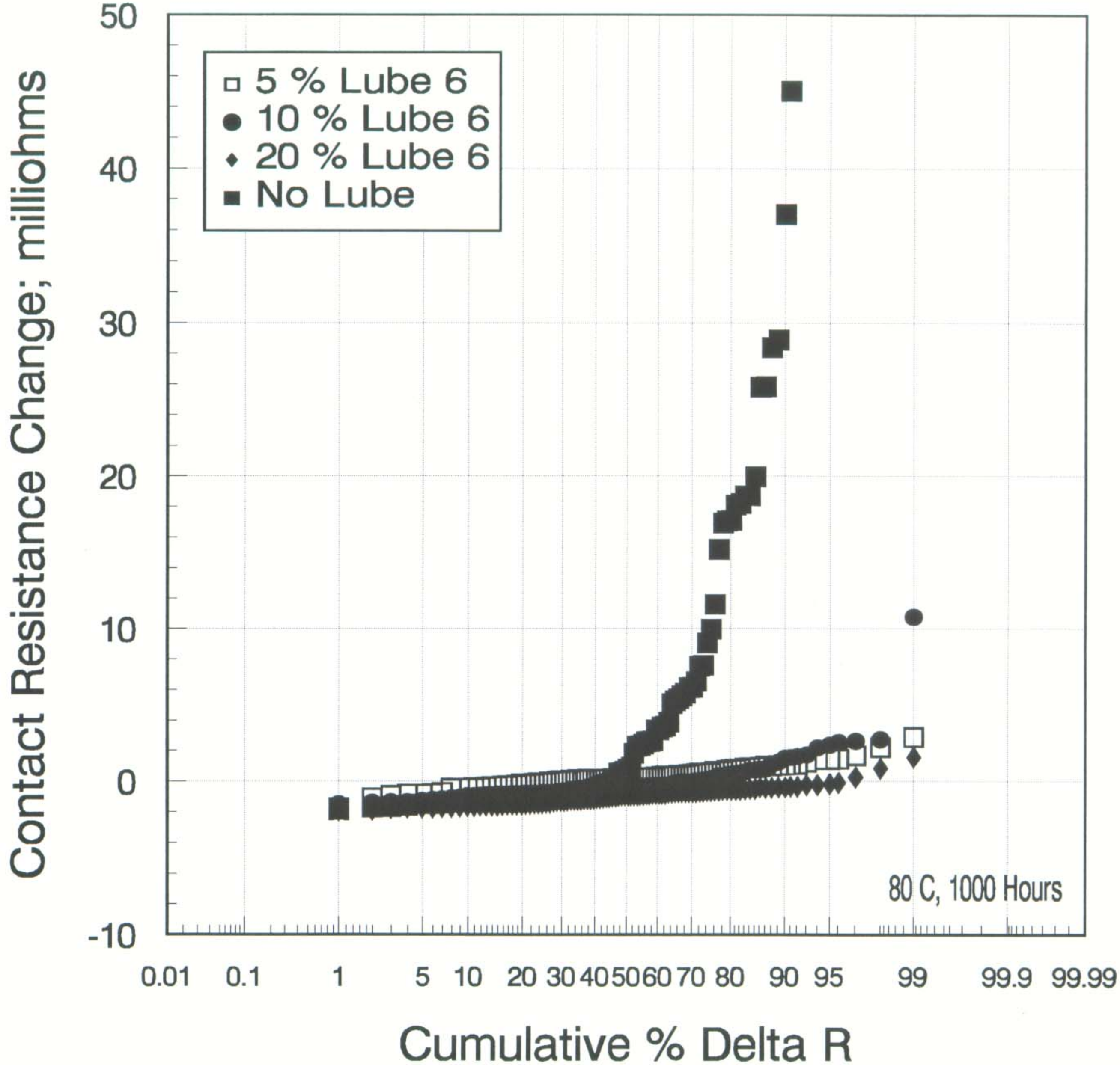

Figure 14. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 80 C THERMAL AGE + 5 DAY

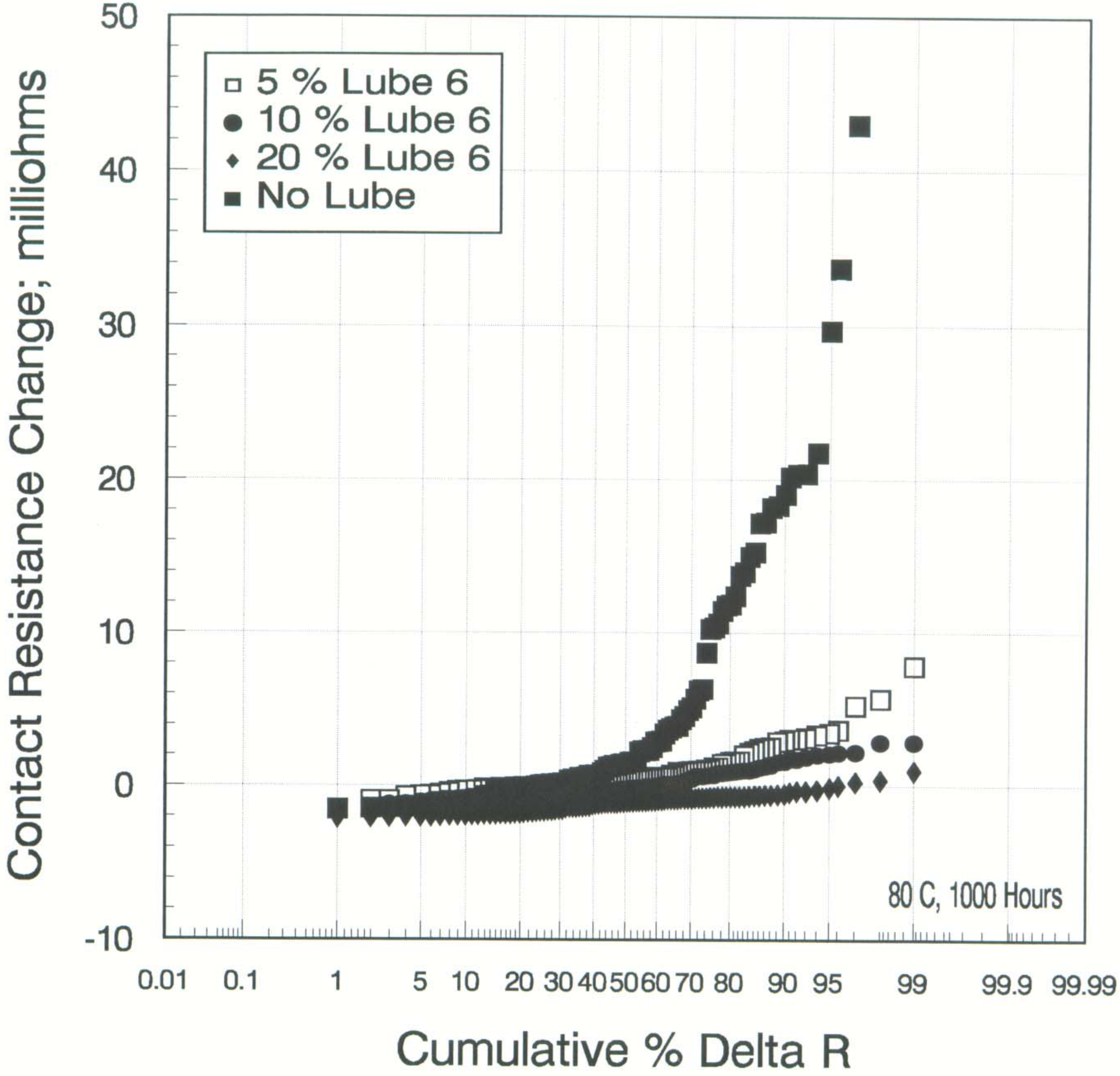

Figure 15. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG GOLD-GOLD CONNECTOR; 80 C THERMAL AGE; 5 DAY + CYCLE

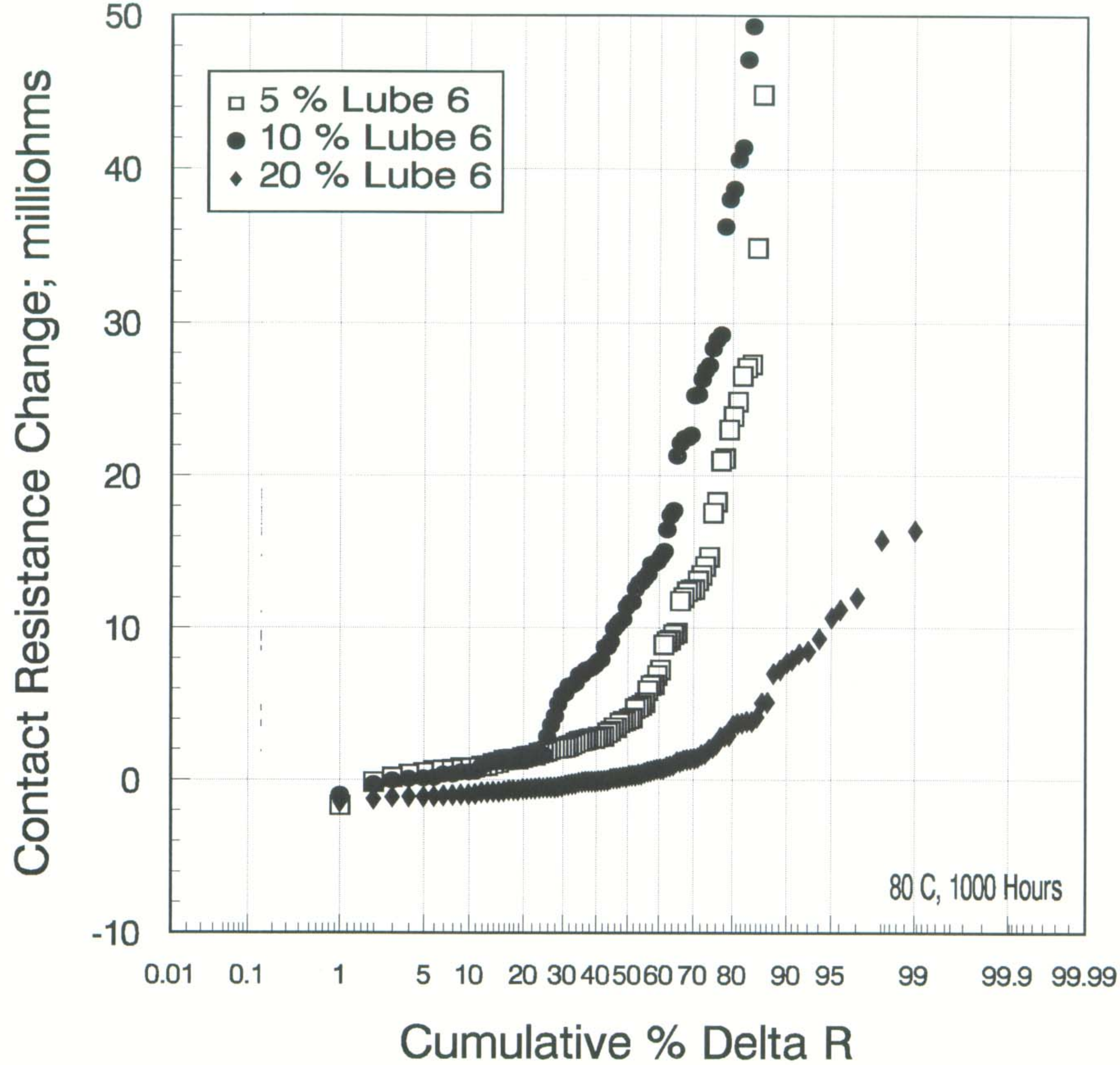

Figure 16. LUBRICANT CONCENTRATION EFFECTS STUDY; CLASS II FMG UNMATED GOLD-GOLD CONNECTOR; 80 C THERMAL AGE + 10 DAY

Appendix I

W. H. Abbott, "Effects of Lubrication on the Reliability of Electrical Connectors,"
(22 pages)

May 5, 2000

Mr. Ronald Taylor
Staff Engineer
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Dear Mr. Taylor:

This letter is a Final Report from Battelle on the results of a study recently completed for Allied. The subject of the study was "Effects of Lubrication on the Reliability of Electrical Connectors".

Background

In late 1998, a study was completed for Sandia on the use of a particular type of lubricant to inhibit the corrosion of porous gold coatings as may be found on electronic connectors. The basis for that work was studies conducted for the Air Force on lubricants conforming to two military specifications. These are MIL-C-81309E and MIL-L-87177A.

The Air Force studies yielded very positive results and even for connectors exposed in very severe environments. In that work, however, the data were obtained with C.O.T.S materials applied as aerosols from spray cans. This meant that the lubricants were applied at high concentrations and in a somewhat uncontrolled manner. The latter was actually intended as a test for field application of the lubricants. Even though those results were very favorable, the results may not be applicable to lubrication in a manufacturing operation.

In view of this situation, a subsequent and very important study was recently completed for Sandia. This study examined the performance of one of these lubricants (MIL-L-87177A) but with application conditions much closer to the needs of a manufacturing operation. Specifically, the study defined the effects of both a volatile carrier and lubricant concentration on corrosion inhibition. Those results clearly indicated important effects but also demonstrated that a lubricant of this type can be applied in a manner consistent with manufacturing needs.

The work just discussed involved studies on the standard Battelle connector test vehicle, which has been used in all work, conducted to date. This was done both for consistency and experimental convenience. However, the work did clearly establish both a desirable carrier and concentration for the lubricant.
It is recognized that the types of connectors of particular interest to Allied and Sandia are various pin and socket types. Therefore, a logical step in this investigation is to extend the work to actual connector hardware. This must involve not only similar performance studies but must also involve the practical questions associated with lubricant application in a manufacturing environment. The latter involves such issues as placement of lubricants in sockets and a variety of thermal exposures.

It is these practical issues that were the subjects of the present studies.

Experimental Studies -- Overview

Lubricant

This work involved one lubricant formulation as the primary material of study. This will be the MIL-L-87177A at a concentration of 5 and 20 weight percent in a volatile carrier of HCFC 141-b. The 20% formulation is probably close to an optimum as defined from the earlier studies. However, that work also showed that even lower concentrations are very effective. Therefore, the 20% concentration was regarded as primary with the 5% formulation included in selected studies as a backup to allow for the possibility of adverse effects from the higher concentration during thermal ageing.

The lubricant(s) just described were obtained from one vendor. This was Lektro-Tech of Tampa, Florida. Actually, the lubricant was obtained as a concentrate from this vendor and it was this form of the lubricant that was diluted to the desired concentration at Battelle.

It is recognized that there are two vendors for the 87177A materials. The fact that one of these was emphasized does not imply any particular bias towards either. The selection was a matter of convenience, since the materials needed were immediately available at Battelle.

Specifically, the concentrate was regarded as the "100%" level even though it was known that this was strictly not the case. This is reported as a matter of record, since it was known that the concentrate/solution already contained some level of HCFC 141b. Therefore, the actual concentration of the active lubricant had to be somewhat less than 5 or 20%.

This subject is reported in some detail, since late in the program a lubricant sample from the second vendor (ILFC) was supplied to Battelle from Sandia. This sample was labeled as a 20% solution, but no details were provided to describe the actual formulation. It is suspected that the actual concentration was less than the 20% primary formulation described above, and it is likely that this was the reason for its lower effectiveness for corrosion inhibition.

Connectors

In this work, the test vehicle was an actual connector assembly of interest to Allied. This was a Bendix SA 1386-3, 18 pin male. Both the pins and sockets were described as having a standard 50 micro-inch gold over-nickel plating. This was not independently confirmed by Battelle.

Allied provided both halves of the connector assembly. Battelle was responsible for all of the wiring to measure these samples.

Lubricant Application

In previous work, the lubricants were typically applied by dipping or spraying methods. It was recognized that these methods may not be desirable in a production environment. Therefore, one of the objectives in this work was to evaluate alternate methods of lubricant application and specifically methods that could be used for mass lubrication of pins and sockets. The procedure finally adopted is described in a following section that describes the various tasks as originally proposed.

Other Experimental Details

All features of the work were similar, if not identical, to the previous work. Specifically, in the laboratory corrosion studies the Class II FMG environment would again be used.

Summary of Proposed Tasks

The following is a summary of the various tasks, which were proposed together with a brief background for each.

Task 1 – Lubricant Application Methods

It is recognized that the application methods used in the previous studies – spraying and dipping – may not be suitable for Allied's manufacturing operations. Ideally, an application method should be available in which lubricant can be selectively and quickly applied to all of the pins and/or sockets in a connector. This should be done without excessive lubricant getting onto the connector housing. While the latter should have no adverse functional effect, it would, at a minimum, pose a cosmetic problem.

In view of this stated need, the objectives of this portion of the work would be to 1) examine methods by which lubrication can be applied, and 2) examine whether such minimal amounts of lubricant will give good corrosion protection.

This problem was approached with the assumption that the amount of lubricant actually required to provide corrosion inhibition is quite small. Also, it was assumed that the amount required within a socket could be transferred even by a natural insertion mechanism such as from lubricated pins.

These assumptions have lead to two proposed approaches for practical lubrication. Both would utilize actual but modified connectors as the vehicle for lubricant application. The obvious advantage of both approaches is that there would be nothing abnormal associated with the required mating of the connectors which might otherwise introduce some form of contamination and/or wear.

The first approach studied utilized lubricated gold pins in an actual male connector. This connector would be modified only by having the plastic shroud machined away to leave the gold pins retained in the plastic base and with their natural alignment. These pins would be lubricated by dipping to a depth of about half the pin length to avoid lubricant buildup on the plastic. This vehicle would then be inserted into a test socket in an attempt to transfer a small quantity of lubricant by this natural process.

The second approach is somewhat more involved but would provide a more controlled and positive means for lubricant injection into the socket cavity. Again it would utilize the male pins as described above. However, in this case the pins would be center drilled from the solder cup side to provide something similar to a mass "hypodermic needle". Some initial experiments have already been made at Battelle to demonstrate that the required fine holes can be accurately placed and without damage to the pin tips.

Some experimental work was required to determine an appropriate means for lubricant injection using this device. It is unlikely that this can be done simply by gravity due to capillary retention forces inside the fine hole. Therefore, it is likely that a device will be fabricated on the backside of the connector to provide the means for controlled injection.

The initial work in this project rapidly lead to the conclusion that the second approach not only could be used, but it also proved to be the most practical for the rapid lubrication of large numbers of pins and sockets.

The relatively simple test fixtures that were developed are shown in Figure 1. Both fixtures used actual male or female connectors. Each was permanently mounted to a stainless steel reservoir onto which a plastic syringe was sealed. A small hole (1/64") was drilled through each pin or socket to provide the route by which lubricant could be injected from the syringe.

In operation, the procedure that was finally adopted was as follows. The appropriate fixture from Figure 1 was oriented in a vertical position such that the ends of the pins or sockets were pointed upward but without the connector to be lubricated. Then the syringe was moved to form a small bubble of lubricant at the tip of each pin or socket.

Initially, this required some experimentation to gain a "correlation" between plunger movement, lubricant appearance, and uniformity among pins (or sockets). Fortunately, it appeared that this technique did provide lubricant appearing on every tip.

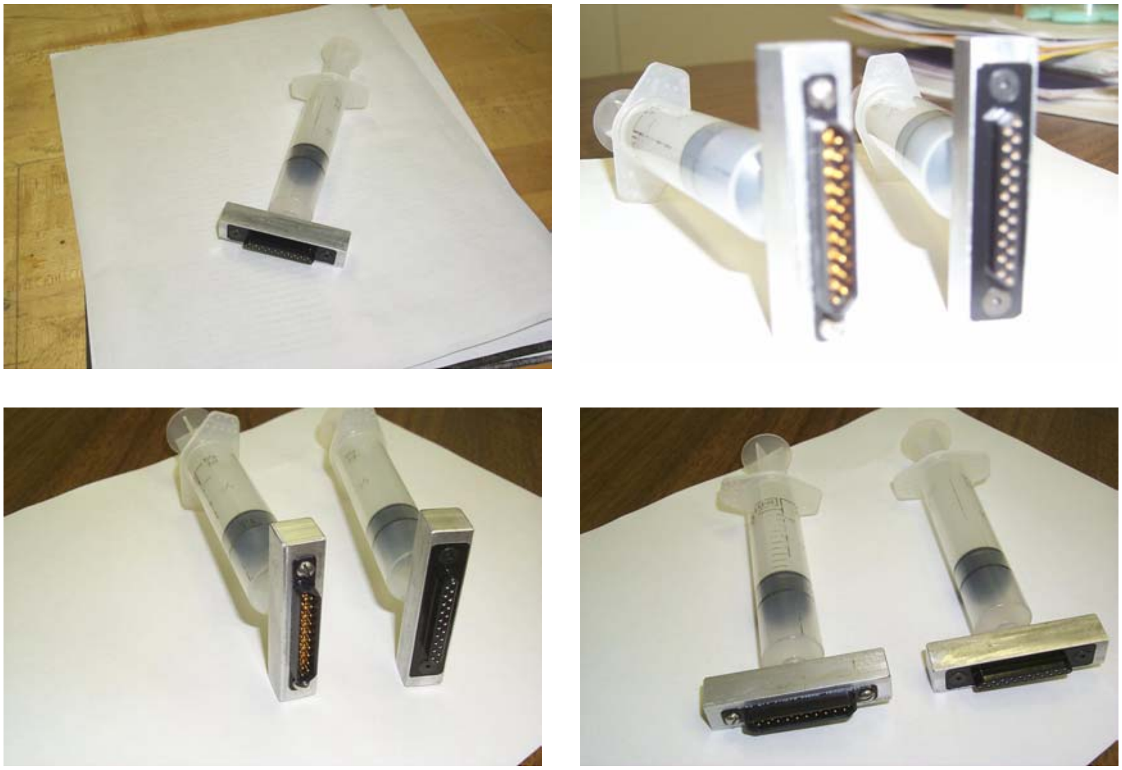

Figure 1. Photos of Test Fixtures Used For Mass Lubrication of Pins and Sockets

Once the presence of lubricant was established, the connector to be lubricated was mated to the test fixture. It remained in this position for only a very brief period of time (seconds). After this half of the test connector system was lubricated, it was removed and the procedure was repeated with the second fixture for the other half of the connector. The two connector halves remained unmated for no more than several minutes before they were mated to form the test connector system.

Task 2 -- Thermal Effects

The objective of this task was to duplicate earlier studies to determine whether there is any evidence of thermal degradation on an actual product, which may affect performance. Earlier work was done on a test vehicle with a relatively high normal force (200+ grams). It is likely that the normal force on the "actual" connectors will be much lower and that this is the critical variable. This work was of further importance, since it should define any potential problems with the 20% concentration.

The aging conditions were proposed as 100 C for 1000 hours with periodic contact resistance measurements. These conditions were used prior to the FMG corrosion exposures.

Task 3 – Transient High Temperature Effects

It is known that connectors will experience short, high temperature excursions during manufacturing when soldering operations occur. Therefore, when a lubricant is already present on the contacts as to obtain shelf life/storage protection then a possibility exists that these events could lead to lubricant degradation. The objective of this portion of the study would be to evaluate this possibility and hopefully to dismiss it as an area of concern.

Originally, it was expected that information would be provided by Sandia or Allied regarding appropriate temperature/time conditions. However, when this information was not available, it was agreed that such information would be determined experimentally at Battelle.

The approach was rather straightforward. Thermocouples were inserted to the bottom of 10 sockets on an actual connector. A small electric soldering iron was preheated as for an actual soldering operation after which solder was applied to the solder cups in a normal procedure. During this operation, the soldering iron was held against the cup for periods between 5 and 10 seconds.

During the soldering operations just described, the thermocouple readouts were observed on a digital readout and recorded on a strip chart recorder. From these experiments it was determined that the transient heating and cooling was very rapid with time at temperature measured in a few seconds. The maximum temperature ever recorded was 185 C.

As a result of these data, the following procedures were adopted to simulate the worst – case time-temperature exposures. The connectors were lubricated as described above. A forced circulation, temperature chamber was preheated to 185 C. The unmated connectors were quickly placed in the chamber and allowed to remain for 1 minute before they were removed to the lab air environment.

The 1-minute exposure was not entirely arbitrary but did provide some margin for a worst-case exposure. An experiment had been conducted in which instrumented connectors were inserted into the chamber in this manner. It was determined that a temperature of 180-185 C was typically reached within 30-40 seconds.

Task 4 – Short Term, High Temperature Service

Sandia has indicated that service conditions may exist in which the products may experience temperatures >105 C for periods of a few hours. The value of 105 C is mentioned, since this is the temperature limit to which Battelle has studied these lubricants.

Subsequent communications from Sandia indicated that actual requirements were probably more like a maximum of 90-95 C and then for periods of no more than several hours. However, Sandia also suggested that a temperature of 125 C might be studied only because this value was mentioned in military specifications. As a result of further discussions, conditions of 125 C for 8 hours were selected for these studies which were conducted on mated connectors.

Task 5 – Field Studies

Battelle recommended that samples be placed at some number of field sites as a definitive demonstration of lubrication effects. This work would be particularly important, since it would complement earlier work in two important ways. First, this work would be done on real connector hardware of direct interest to Allied and Sandia. Also, it would be the first field test of the reduced concentration lubricant.

Battelle also recommended a minimum of two (2) field sites for consideration. Those sites were proposed to be the Indoor and Outdoor (sheltered) sites at Battelle's Daytona Beach facility. There are a variety of technical and procedural reasons for proposing these sites, but probably the most important is that there is already a large body of test data at these sites for comparison from earlier Air Force studies.

We further proposed to place both lubricated and unlubricated connectors at these sites. These would remain in place for a period of 1 year. However, since it was convenient for us to quickly return these samples for measurement, we proposed to obtain quarterly test data on them.

Experimental Results

Effects of Soldering

The results from these experiments are summarized in Figure 2. The conclusion from these data is that there is no evidence of degradation of either the 5 or 20% lubricant mixtures as a result of the thermal exposure which may result from typical soldering operations.

It should be noted that these data do not address the question of whether lubricant was removed (such as by volatilization) as a result of this thermal stress. This question should be answered by the results of corrosion exposures on these samples as reviewed in a following section.

Effects of Thermal Ageing

The results from these experiments are summarized in Figure 3. The conclusion from these data is that there is no evidence of degradation of either the 5 or 20% lubricant mixtures as a result of the thermal exposure which may result from typical soldering operations.

It should be noted that these data do not address the question of whether lubricant was removed (such as by volatilization) as a result of this thermal stress. This question should be answered by the results of corrosion exposures on these samples as reviewed in a following section.

Corrosion After Short-Term Thermal Ageing

The samples used to generate the data for Figures 2 and 3 were next subjected to unmated exposures in an FMG (Class II) exposure. The purpose of this work was to determine by inference whether the lubricant had either been changed or depleted to an extent that there was no longer adequate corrosion protection.

The points of reference would be the earlier work conducted for Sandia which demonstrated that the 20% lubricant formulation will provide almost total corrosion inhibition. Furthermore, even the 5% concentration provided a high degree of protection.

This conclusion must be qualified by the fact that the earlier work was done on a different connector system in which the average contact normal force was presumably higher than on the present connectors. However, data were developed in this study which will demonstrate the corrosion susceptibility of the present connector system and lubricant effectiveness.

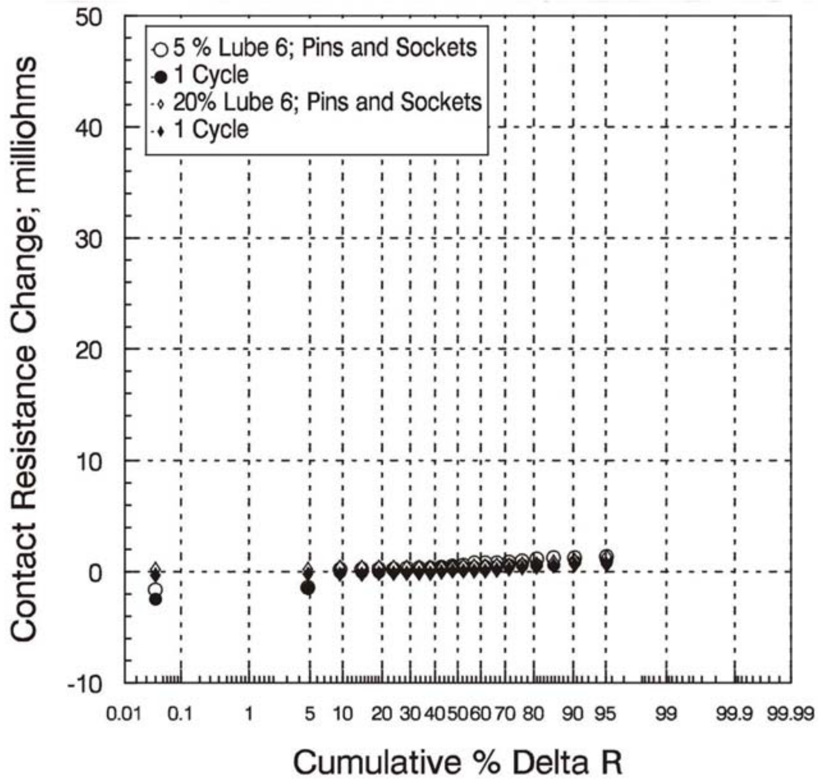

Figure 2 Effects of Heat Ageing By Soldering On
Contact Resistance of Lubricated Connectors

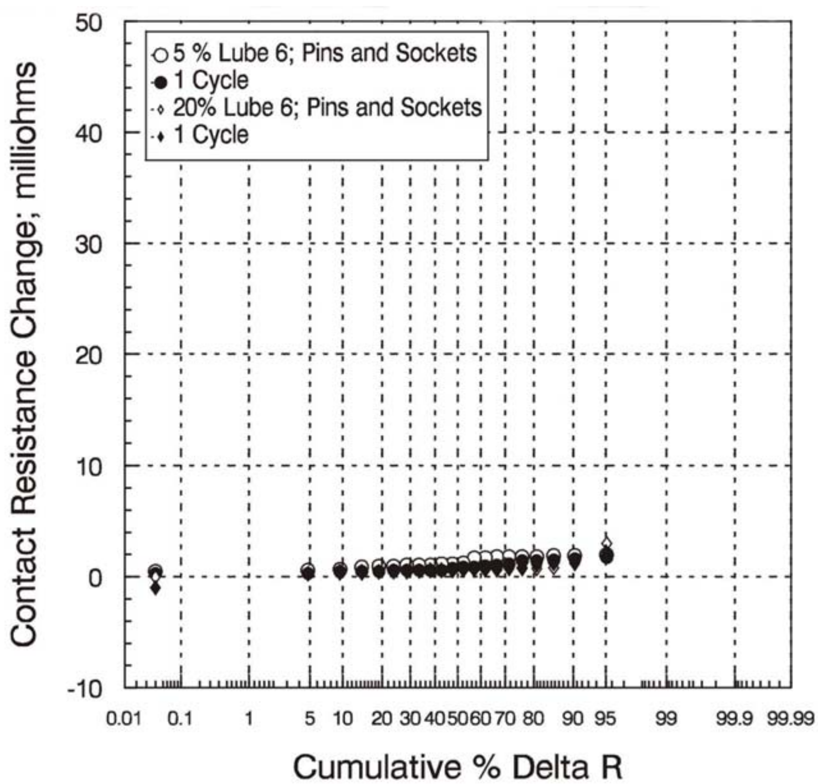

Figure 3 Effects of Heat Ageing (125 C, 8 Hrs) On
Contact Resistance of Lubricated Connectors

The results of the FMG exposures on the soldered and 125 C aged samples are summarized in Figures 4 through 7. For reference purposes, Figures 8 through 10 in the following section should be viewed.

The results of Figures 4-7 indicate that there was a slight loss of lubricant effectiveness as a result of the soldering operation. This conclusion is based on the data for the 20% lubricant formulation. Earlier data indicated that the 5% lubricant level was marginal or inadequate to obtain corrosion protection for unmated exposures of this type. Therefore, the data in Figures 4 and 6 are not surprising.

The results of Figures 5 and 7 clearly show that even relatively short (8 hour) exposures at 125 C appear to result in lubricant loss to a degree that corrosion inhibition may be reduced. This result is actually not too surprising in view of earlier Battelle studies which have concluded that for most lubricants of this type a temperature of about 105 C represents the limit for extended thermal ageing and corrosion protection.

These conclusions are of some significance regarding future qualification and even application of these materials. Earlier, it was noted that inputs from Sandia suggested that the maximum temperature requirement in applications might be no more than 95 C. If this were the case, then past data and data in the following section would indicate that there is no real thermal ageing problem with these materials. However, requirements for **qualification** at 125 C may present a limitation depending on the specific requirements. For example, Figure 3 would suggest that the lubricants could be subjected to short term thermal ageing at 125 C. However, if a corrosion inhibition or other similar functional test may be required after such ageing, it might be difficult to qualify the lubricant.

Corrosion After Long-Term Thermal Ageing

Additional experiments were conducted in which the lubricants were applied 1) only to pins, 2) only to sockets, and 3) both pins and sockets. The samples were mated once. Then they were subjected to thermal ageing at 100 C for 1000 hours in the mated condition. After the thermal ageing, the same samples were exposed to the Class II FMG environment in the unmated condition as a worst case test of lubricant effectiveness.

The purpose of these experiments was to examine more realistic thermal requirements and to test the thesis that the lubricant could be effectively dispersed to both surfaces even if it were applied to only one.

There was one further objective of this work. This was to examine the relative performance of the lubricants from the two vendors at the “20%” concentration. Reference should be made to an early section of this report for a more detailed discussion of this subject that also raises the question of whether the two concentrations were really the same.

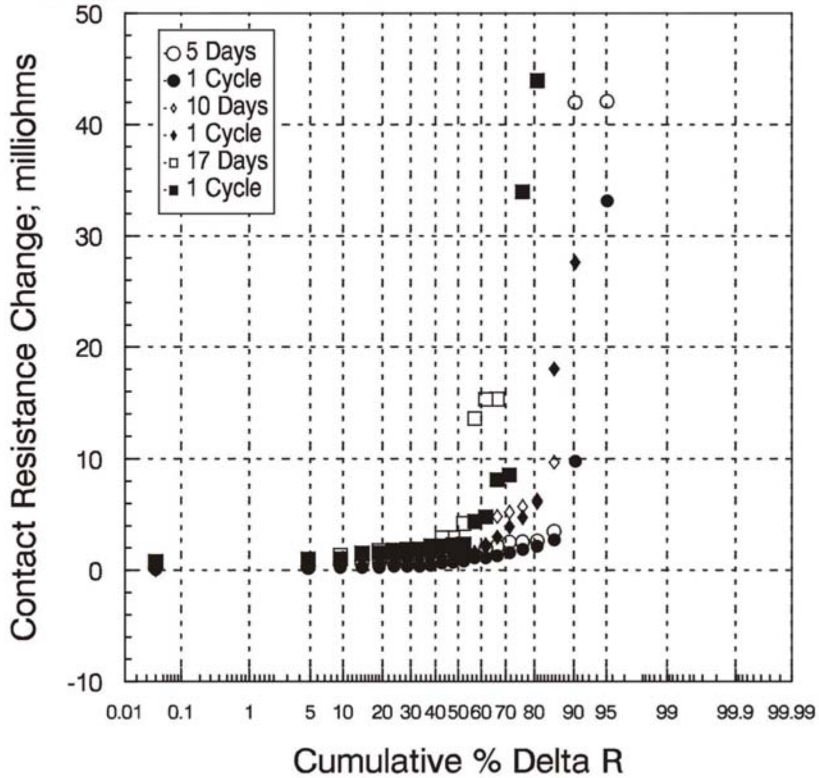

Figure 4 Class II FMG Exposure of Unmated Connectors After Lubrication (5%) And Soldering

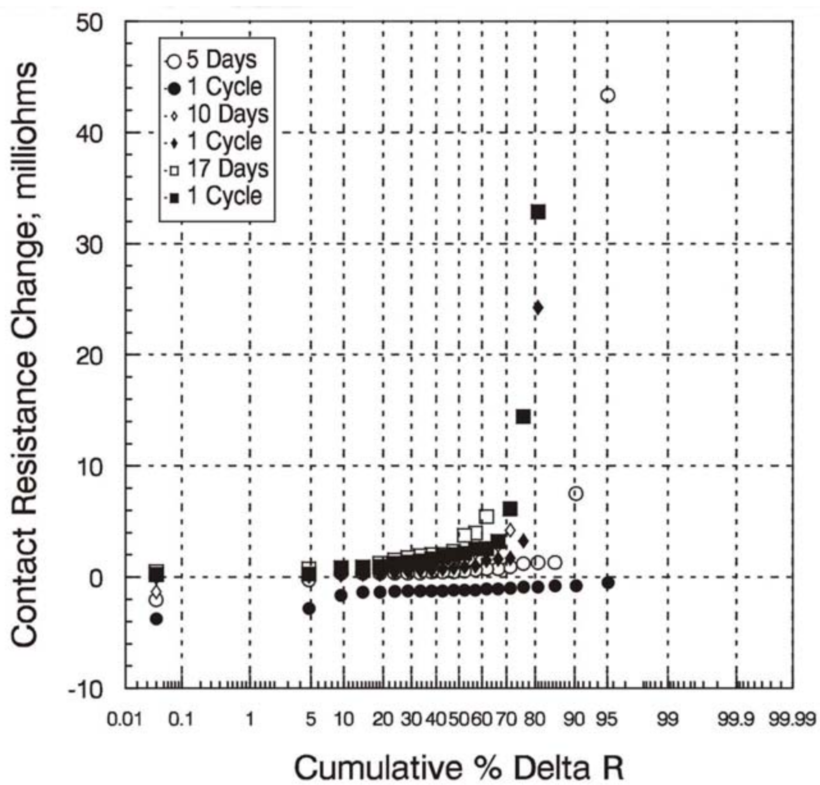

Figure 5 Class II FMG Exposure of Unmated Connectors After Lubrication (20%) And Soldering

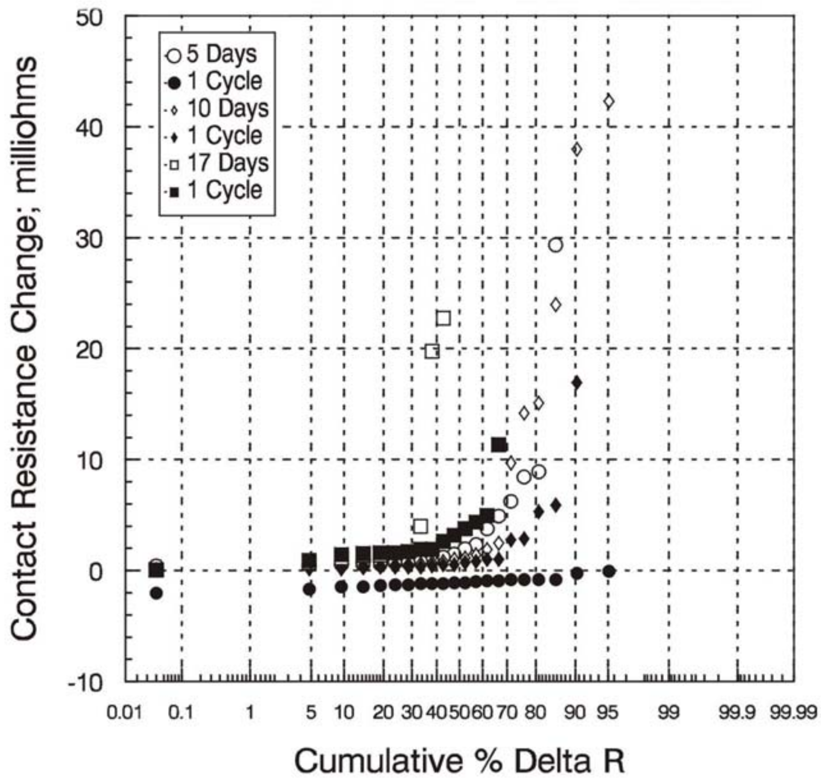

Figure 6 Class II FMG Exposure of Unmated Connectors After Lubrication (5%) And Heat Ageing (125 C)

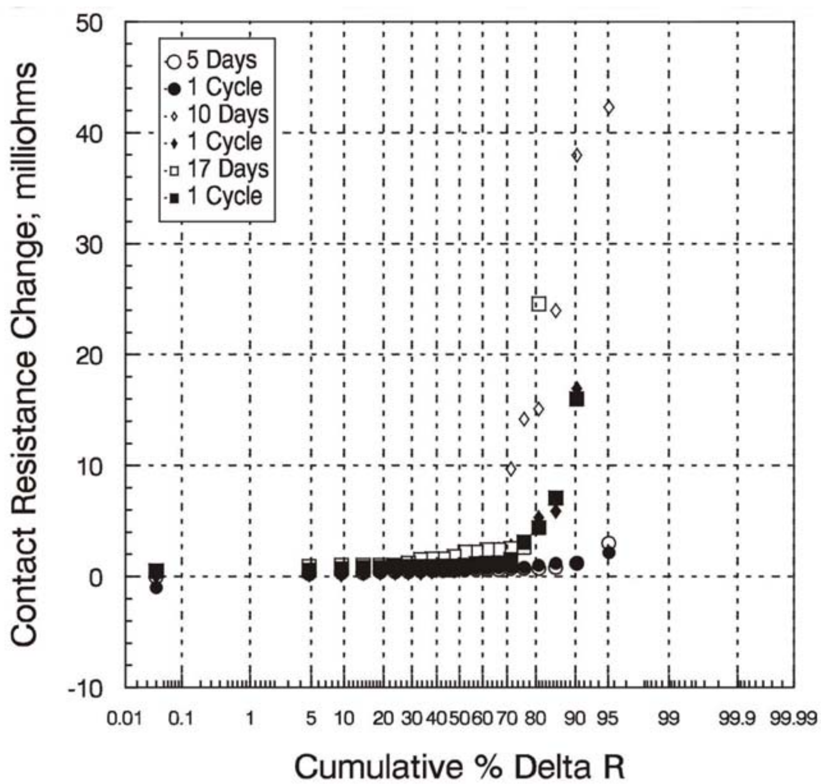

Figure 7 Class II FMG Exposure of Unmated Connectors After Lubrication (20%) And Heat Ageing (125 C)

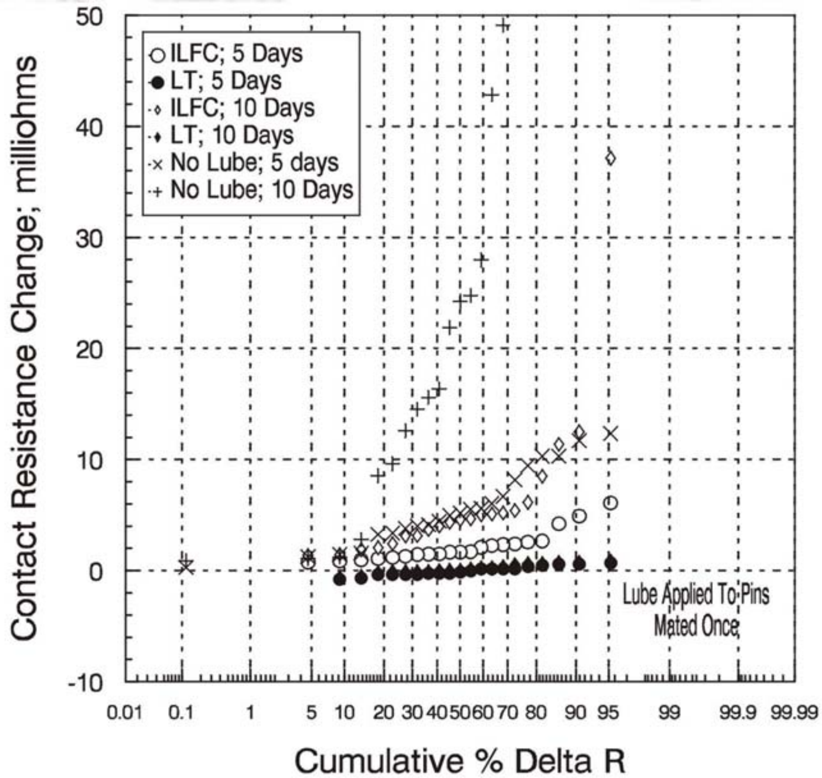

Figure 8 Corrosion Of Unmated Connectors In Class II FMG
Lubricant Applied By Mass Lubrication Device
Comparison Of 20% ILFC And 20% Lektro Tech

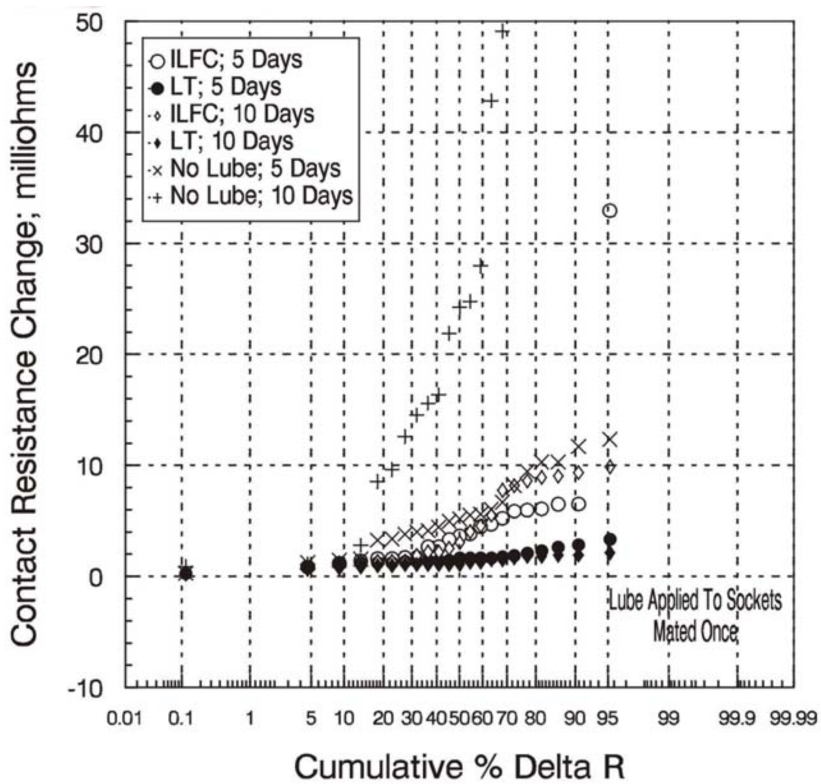

Figure 9 Corrosion Of Unmated Connectors In Class II FMG
Lubricant Applied By Mass Lubrication Device
Comparison Of 20% ILFC And 20% Lektro Tech

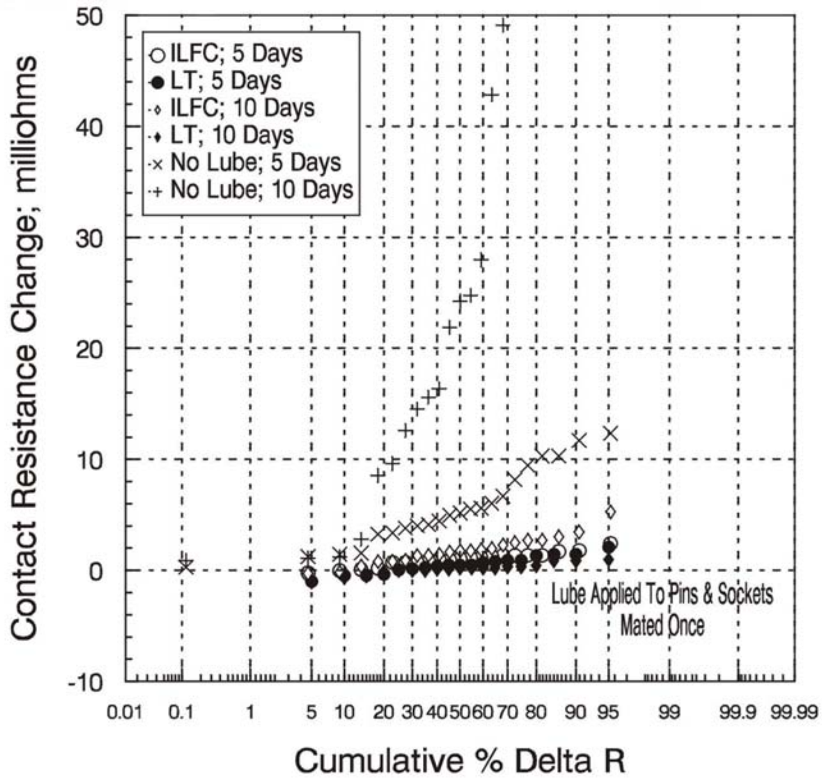

Figure 10 Corrosion Of Unmated Connectors; Class II FMG
Lubricant Applied By Mass Lubrication Device
Comparison Of 20% ILFC And 20% Lektro Tech

The results of these experiments are shown in Figures 8 through 10. A large amount of potentially very important information is shown. First, the data confirm that the 20% formulation of the lubricant designated as LT (Lektro-Tech) does provide almost total corrosion inhibition and does so even after thermal ageing at 100 C. These data are in agreement with earlier studies, but the present data have extended these results to this connector system for which the critical difference is probably a lower contact normal force. These conclusions strongly reinforce the view that any qualification requirements should begin to match the worst case use requirements.

The data also appear to show that the ILFC lubricant was not as effective as the LT even though it clearly did reduce corrosion compared to the unlubricated condition. The differences between these two materials were discussed earlier . It might be added that there is circumstantial evidence from just the appearance of the samples that the formulation of the ILFC lubricant provided from Sandia was substantially less than 20%. This is the most probable explanation of the differences shown particularly in Figures 8 and 9. Therefore, it is also probable that if these two lubricants were actually evaluated at the same concentrations the performance would be similar.

A second conclusion from this work involves the issue of lubricant dispersion. The data indicate that it may be quite sufficient to apply lubricant to only one half of a connector system to get adequate protection on both halves. This conclusion is in agreement with earlier results that have suggested only a very small amount of lubricant on a surface is sufficient to provide a high degree of protection. Larger amounts provide little added benefit but at least do not have adverse effects.

The third conclusion from this work is the rather clear demonstration that the actual product used in this study is potentially susceptible to corrosion. In fact, it appears that this connector system would not meet current requirements, for example, for tests of modern telecommunications connectors such as those found in Bellcore GR-1217. These comments are added for information only and do not indicate that these connectors will degrade in service, since they will likely be in a mated condition. At the same time, these data suggest that if the local environment is sufficiently severe and can ingress into the connector interface, this plating system can corrode.

Field Site Corrosion

Data for the lubricated and unlubricated connectors exposed at two field sites over a 1 year period are shown in Figures 11 through 17. These data are potentially of great importance, since they demonstrate lubricant effectiveness on an actual connector system and for the new method of lubricant application. It is important to recognize that these data were obtained only for the 20% LT (also referenced as Lube 6 per earlier work). No conclusions can be drawn regarding what the performance of lower concentrations of the LT or the ILFC material might have been.

Two environments were studied and it is useful to place these in proper perspective. Both were run at the Battelle Daytona Beach facilities. One location was an uncontrolled, indoor environment. According to Battelle monitoring data, this site qualifies as a high Class II site. This definition is important, since some available data for Sandia applications would indicate that the typical operating/storage environments are no more severe than Class II. Since the degradation rate of the connectors was expected to be low in this environment, a decision was made to use only a worst case condition of unmated exposures. Both halves of the connectors were lubricated and exposed.

The second site can best be described as a sheltered, outdoor exposure located about 150 meters above mean high tide line. This site is quite severe and rates as Class IV. It is unlikely that Sandia applications would be in environments this severe, but at the same time successful exposures in a site this severe would represent an important demonstration. In this case, a decision was made to run both mated and unmated connectors.

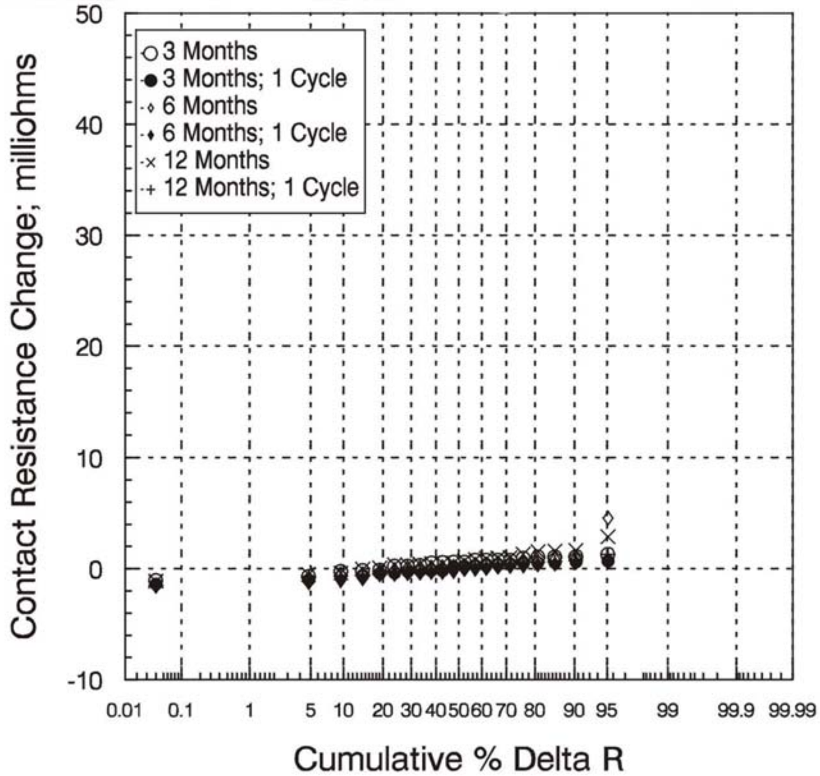

Figure 11 Corrosion Of Unmated Connectors In Field Indoor Class II Environment; No Lubrication

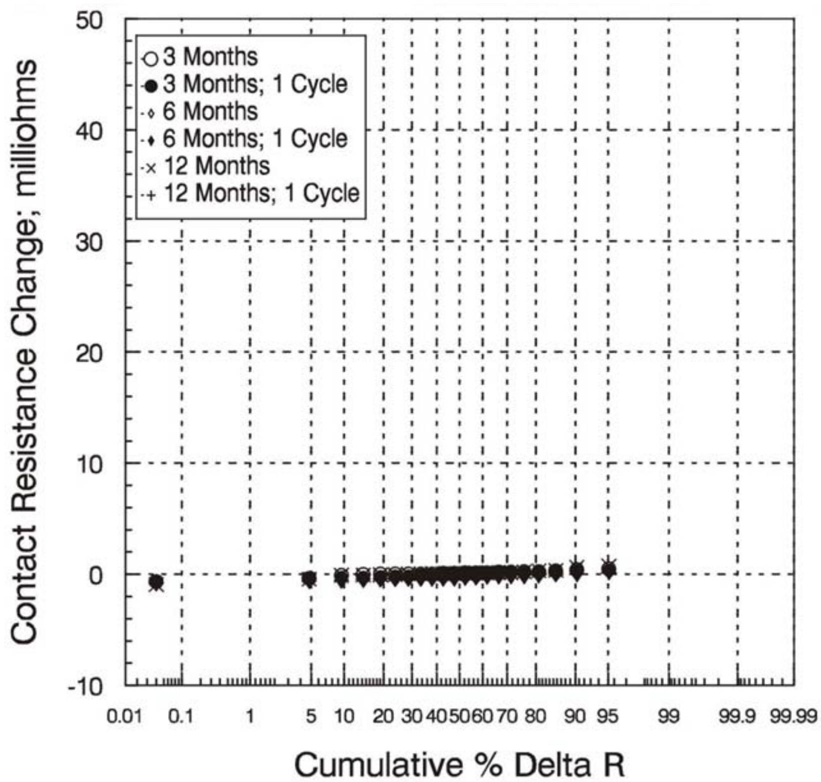

Figure 12 Corrosion Of Unmated Connectors In Field Indoor Class II Environment; 5% Lube 6

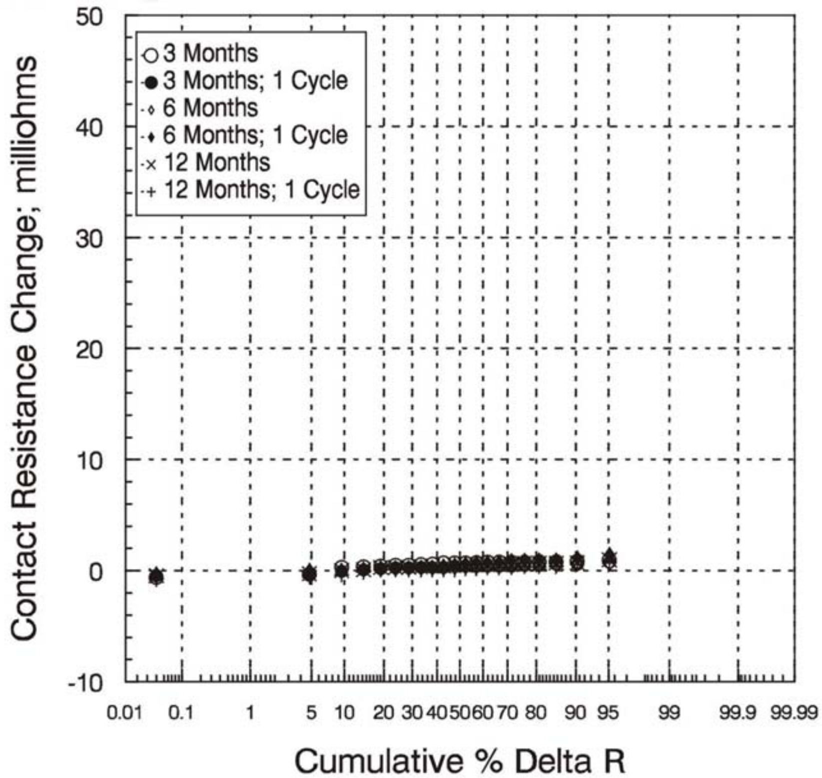

Figure 13 Corrosion Of Unmated Connectors In Field
Indoor Class II Environment; 20% Lube 6

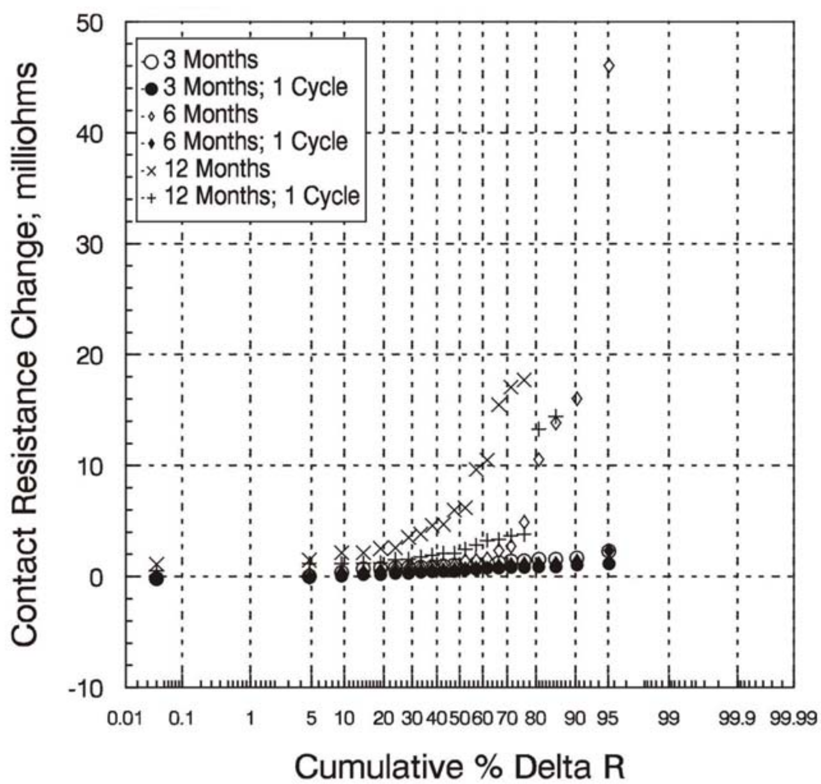

Figure 14 Corrosion Of Unmated Connectors In Field
Sheltered Outdoor Class IV Environment;No Lube

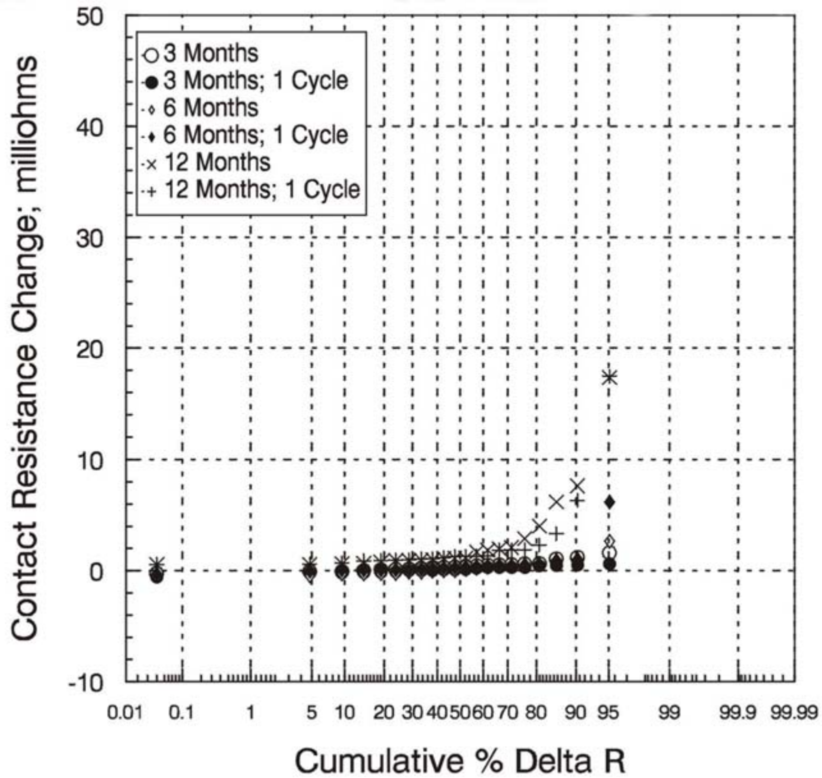

Figure 15 Corrosion Of Mated Connectors In Field
Sheltered Outdoor Class IV Environment; 5% L6

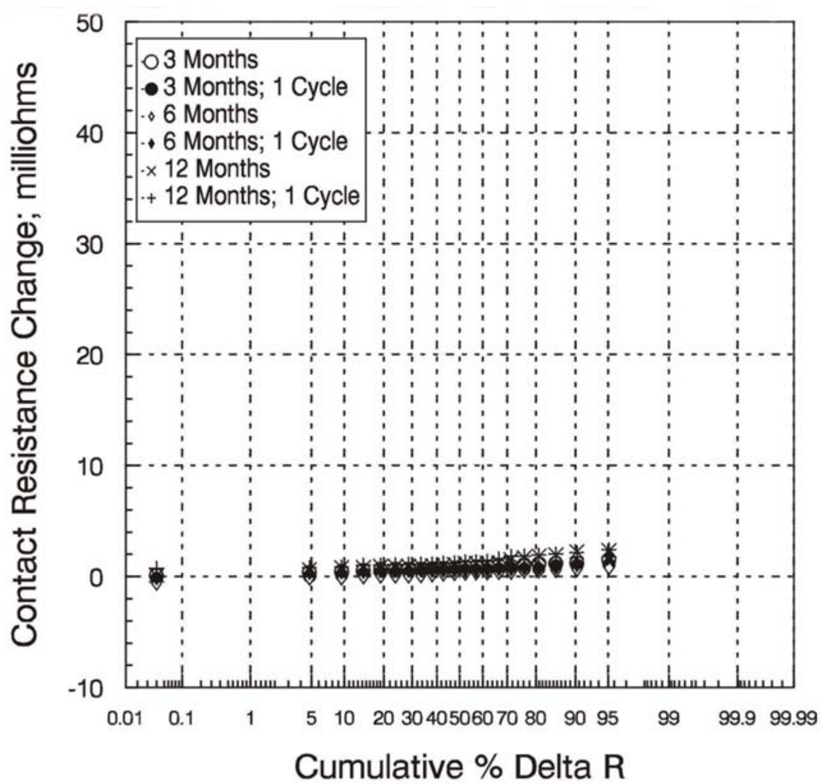

Figure 16 Corrosion Of Mated Connectors In Field
Sheltered Outdoor Class IV Environment; 20% L6

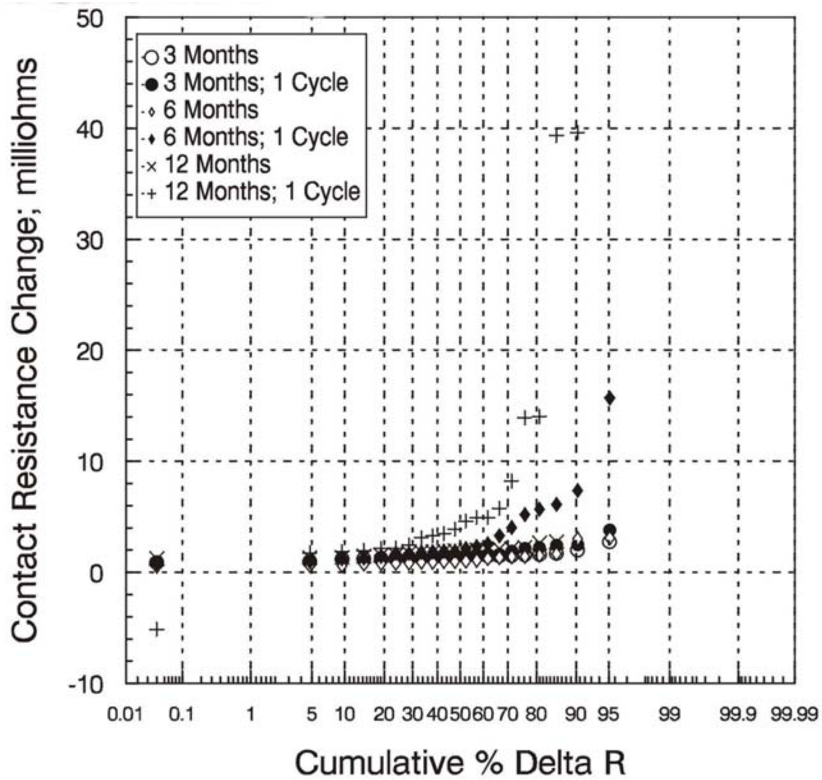

Figure 17 Corrosion Of Mated Connectors In Field Sheltered Outdoor Class IV Environment;No Lube

Figure 11 shows the results for the unmated, indoor exposures on connectors without lubrication. These data indicate the beginnings of degradation within the 6-12 month time period. Although the effects were measurable, the extent of degradation had not progressed to a level that would normally be considered as a failed/high risk state.

Figures 12 and 13 show the effects of both the 5 and 20% lubrication levels. These data are important in two respects. First, the data show that complete protection was achieved at both lubrication levels. These data indicate that even the 5% level **might** be adequate in such environments. At the same time, the earlier data would tend to favor the higher concentrations.

The second feature in these data may address the question of possible effects of dust. This concern is frequently raised in connection with the use of lubricants. These connectors were exposed in a location with noticeable dust collection typical of uncontrolled environments. In spite of this, the absence of any change in the electrical data tends to confirm earlier conclusions by Battelle that at most dust effects may be only cosmetic in nature.

Figures 14 through 17 show the results for the more severe outdoor exposure. Figure 14 confirms that without lubricant protection this connector system will degrade rather quickly in this type of environment. These data were for the unmated condition and it was not too surprising that they did degrade.

It is, therefore, fortunate that a separate mated connector system was also exposed. These data are shown in Figure 17, and it is somewhat surprising that for this condition there was a significant degree of degradation even within 6 months! Apparently, this particular design does not provide the degree of shielding and corrosion attenuation that was "expected". These are relatively new and potentially important findings.

Figures 15 and 16 show equally important data which tend to support the results of the lab studies. They show that both lubricants will attenuate corrosion. However, the 20% level is clearly favored in order to achieve complete corrosion protection. The 5% level is not adequate. No extrapolation of data can be made between the 5 and 20% concentration effects. While the 20% level appears to be totally adequate, it is not known whether some lower level above 5% would also be adequate.

Finally, these results cannot be extrapolated to the mated condition, and in view of the results obtained for the mated connectors without lubrication it is unfortunate that mated, lubricated exposures were not included. It is reasonable to conclude that for the mated condition the 20% concentration would have produced very favorable results. However, we cannot conclude whether the 5% level would or would not have been adequate for the mated condition.

Conclusions

This study has produced new and important information related to the practical use of a particular type of lubricant on gold plated connectors. The results have indicated that an 87177A type lubricant can be applied in a practical manner and that total corrosion inhibition can be achieved.

The present results would lead to the recommendation of a lubricant concentration in the range of 20 weight percent. While the data indicate that a much lower concentration such as 5% may not be adequate, no conclusions can be reached about intermediate concentrations.

The present results indicate that it should be possible to conduct soldering operations on lubricated connectors with no adverse effects. At the same time, the degree of lubricant loss should be sufficiently low that corrosion inhibition can be retained.

The data have shown that this type of lubricant cannot be reliably used at long term temperatures much above 100-105 C. This is probably a conservative (low) range. While it is possible that somewhat higher temperatures could be tolerated, it is clear that exposures at 125 C are beyond the capabilities of this lubricant type. For this reason, careful consideration should be given to how these lubricants should be qualified in view of the fact that Sandia applications may actually be lower than 100 C aging requirements.

This completes our studies on this interesting project for Allied. If you have any questions on the contents of this report, please let me know.

Very truly yours,

William H. Abbott
Engineered Materials
Advanced Materials Group

WHA:mw

Appendix J

Ronald Taylor “Connector Lubricant Qualification Report”
(5 pages)

Honeywell

Memorandum

Federal Manufacturing & Technologies
Kansas City, Missouri

Date: 01/15/01

To: File

From: Ronald D. Taylor D/462

Subject: CONNECTOR LUBRICANT QUALIFICATION REPORT

Title Page

CONNECTOR LUBRICANT QUALIFICATION REPORT

Abstract:

This report describes qualification testing at FM&T on a lubricant designed for DOE, WR connector applications. This effort is funded by PDP Project #706399 "Develop and Deploy Connector Lubricant". The lubricant tested is MIL-C-87177A based formulation. Other phases of the project have documented the effectivness of the lubricant at minimizing the effects of environmental and fretting corrosion, especially in connector applications using gold on gold contact arrangements. The testing was designed to verify that the lubricant would not have any detrimental impact on the physical or electrical performance characteristics of connector performance. Test conditions were: Low temperature, thermal aging, durabiliity and temperature-Humidity. Contact resistance measurements were used as the standard of performance.

Summary

A PDP project #706399 titled "Develop and Deploy Connector Lubricant" was established at Honeywell FM&T in corroperation with SNLA. The development of a connector lubricant for DOE weapons application is necessary to inhance performance, shelf life, and service life by minimizing the effects of environmental and fretting corrosion. This has become especially critical with the increasing use of COTS parts and Nano connector, which inheriently have thinner platings and are more susceptable to corrosion problems. The formulation for the lubricant, the ideal concentration and the solvents for cleaning have been developed and tested. The effectivness in preventing environmental corrosion and reducing effects of fretting corrosion has been established in earlier phases of the project. This report documents the Qualification work accomplished at FM&T. The goal of this qualification is to establish that the lubricant does not have any negitive effects on the electrical performance after exposure conditions of ; repeated use, low and high temperature and Humidity. New SA type rack and pannel PEEK connectors were used with contact plating of 50 micro in min Au over 50 micro in min Ni. The base line Contact Resistance measurments were monitored on lubricated and unlubricated samples through out the battery of testing. The lubricant passed all tests. No changes in electrical performance were observed in the lubricated parts vs the unlubricated parts.

Discussion

Scope and Purpose

The project to develop a connector lubricant as initiated to help reduce effects of envionmental corrosion ove r time. Several incidents were documented involving parts eight to ten years old that removed from stores and failed visual criteria for corrosion. During failure analysis, it was determined that the rejected parts exceded the minimum plating requirements. These parts are expected to have a twenty year life in the field. The need to enhance the shelf life and service life was obvious. Members of the FM&T and SNLA connector team attended courses on electrical arcs and contacts. Corrosion prevention and lubrication were important considerations on increasing reliablity connectors. Lubrication techniques have been applied in industry for high rel componets for many years and most recently studied, tested and approved for DOD applications. Our goal was to use as much of the current literature and testing results for develop a custom lubricant for DOE applications. It was known that convencing engineers to apply a Dielectric (non conducting material) on electrical contacts of weapons systems would not be an easy task. A PDP Project #706399 titled "Develop And Deploy Connector Lubricant" was initiated. The objectives were to:

- to formulate custom lubricant
- determine optimum concentration
- write a specification
- develop solvent for cleaning
- develop application techniques
- evaluate effectivness for environmental and fretting corrosion protection
- qualify the lubricant
- perform materials compatibility analysis

The project development work has been performed at Battelle Labs, SNLA and Honeywell FM&T

Activity

This report documents the results of the MIL-C-87177A based Connector Lubricant Qualification effort conducted at FM&T. Development work on this project is funded by Adapt project #706399 "Development Of A Lubricant For Connectors".

Previous work on this project has documented the benefits derived from the use of the lubricant. The lubricant has been shown to significantly reduce effects of environmental and fretting corrosion. This battery of Qualification testing is designed to document that the lubricant does not have any negative effects on the electrical performance after repeated use, long term aging or exposure to various temperature and humidity conditions.

Qualification Test Design: Seven pairs of PEEK SA2287-7 & SA2288-7 (21) contact connectors were used. The connectors selected for this testing were manufactured by VISHAY/DALE Yankton, SD, and had been molded with PEEK insulation material. For all of these connectors, individual electrical wires, about 24" long, were soldered to each contact's solder cup on the rear face of the connector. Each of the 147 contacts could then be treated as separate contacts when mated. Lubricant was applied to six pairs of connectors and one pair was left un-lubricated as a control. (126 contacts were lubricated, 21 were not lubricated). The contacts were mated and individually numbered.

Contact Resistance (CR) was determined to be the parameter that would be used to measure electrical performance. Increased contact resistance would indicate degradation in the electrical contact performance. Initial contact resistance measurements were taken and recorded for comparisons with values at the end of the testing.

Testing consisted of the following four test groups.

1. Low Temperature Performance: Lower the temperature from +30 C to –60 C deg. measuring CR every 10 C deg. Repeat measurements on heating -60 C to +30 C deg. measuring every 10 C deg. – Document all (CR) measurements and record (CR) values at the end of the temp cycle testing as endpoints data.
2. Thermal Aging: +100 C deg. for 1000 hours -- measure & record (CR) as endpoints.

3. Durability Cycle: Subject samples to 100 cycles of insertion / withdrawal – measures & record endpoints (CR) data.
4. Temperature – Humidity Mil. Std 202 method 106 (less step 7) +25 C to + 65 C 10 cycles at 85% Humidity – measure and record endpoints CR data.

Analysis of Results:

Visual inspection at the conclusion of the testing revealed the following results:

The inspector commented that all lubricated contacts appeared dirty like they were covered with grease. This was expected and did not affect electrical performance. The lubricant did not appear to adversely affect the PEEK insulation material. There was no evidence of cracking, crazing, srinkage, or other visual criteria that was different from the non-lubricated sample.

The electrical performance:

Ideally we would expect to see either no change or a very minimal increase in the contact resistance values. Which would indicate that the contact performance remains constant and no aging induced corrosion effects were indicated.

Contact Resistance, remained stable at the conclusion of the qualification testing, as compared the pre qual base line (CR) measurements. Post testing, (CR) values, at the end of each battery of tests also remained stable. At final Points testing, every contact had a slightly lower (CR) than the initial value, for both the lubricated and non-lubricated contacts.

This small reduction in (CR) values we attributed to a variation in the test conditions at Pre and Post testing. The lower Relative Humidity (RH) 26% during post testing could provide a minimal reduction in the (CR) readings versus (45%) in the pre test. The test condition requirements are to maintain (50%) or less (RH).

Initial (CR) measurements were in the 92.1 to 93.8 Milliohm range. Final end points measurements were in the 91.5 to 93.1 Milliohm range. The environmental test conditions were **76 deg F** and **RH of 45%** for the initial testing done in Oct 1999, and **73 deg. F** and **RH of 26%** for the final end points done in Dec 1999.

The conclusion drawn as a result of these qualification test is that the lubricant characteristics remained stable and performance did not degrade with exposure to various durability, temperature and humidity conditions.

Previous tests using this lubricant, performed by FM&T, Battelle and SNLA, funded through this Adapt project, have been very encouraging. Data so far has documented significant performance enhancement achieved by the use of this lubricant. During 1-year field studies, exposure to mixed gas environments, life testing and Fretting studies the lubricant has demonstrated that it can significantly reduce effects of environmental and Fretting induced corrosion. Details of these studies will be documented in later reports as the work is finalized.

See attachments for summary of results, charts and raw data.

Ronald D. Taylor D/462 Staff Engineer

SUMMARY OF THE CONNECTOR LUBRICANT

QUALIFICATION RESULTS

Contact Resistance Readings All readings are in MilliOhms

	NON LUB PRE mΩ	NON LUB POST mΩ	LUB PRE TEST mΩ	LUB POST TEST mΩ
	N=21	N=21	N=126	N=126
MEAN	92.60	****92.00***	92.60	****92.05***
STD DEV	0.2350	0.2407	0.3200	0.3200
MIN	92.2	91.6	92.0	91.4
MAX	93.0	92.4	93.9	93.1

* NOTE: The “Post Testing” readings were done 12/99 with the Relative Humidity at 26% RH verses 45% RH for the “Pre Tests” readings taken 10/99 This probably accounts for the slight drop in “Post Test” readings in all of the results.

The test results support our premise that the lubricant does not have any degrading impact on electrical performance after exposure to life, temp cycling, humidity and insertion withdrawal testing.

RDT 1/12/2000

MYDOC lub tech report 1-16-02

Appendix K

Ginger De Marquis, “Final Progress Report (after the last - 150th thermal cycle): Qualification of MIL-L-87177 for Use as a Corrosion Inhibitor and Lubricant on WR Nano-connectors.”
(8 pages)

Sandia National Laboratories
Operated for the U.S. Department of Energy by
Sandia Corporation
P.O. Box 5800
Albuquerque, New Mexico 87185-0523

date: October 25, 2001

to: Distribution

from: Ginger De Marquis, MS-0523 (01733)

subject: **Final Progress Report (after the last - 150th thermal cycle): Qualification of MIL-L-87177 for Use as a Corrosion Inhibitor and Lubricant on WR Nano-connectors.**

Executive Summary: Throughout this study, there were no functional failures on either boards or connectors. Additionally, there was no significant amount of lubricant found in the head-space gas from any of the canisters, nor was any significant amount of lubricant found on the glass slides (representing optical windows). The presence of lubricant had no affect on the ability of the DEB hydrogen getter to take up hydrogen.

Materials and parts underwent 150 thermal cycles ranging from 71^{o}C to –40^{o}C in sealed canisters. Functional boards with nano-connectors, key questionable materials (i.e. DEB getter) and glass slides were thermal cycled in canisters with and without the lubricant. After every 25 thermal cycles:

- The boards were functionally tested.
- The gas in the canisters was analyzed for trace lubricant and/or degradation products of the lubricant.
- Glass slides were extracted with solvent and analyzed using mass spectroscopy to determine whether or not the lubricant would migrate and condense onto other surfaces.
- DEB getter material was analyzed to determine its ability to take up hydrogen.

Conclusion: The results of this study demonstrate that MIL-L-87177 does not interfere with the functionality of certain electrical components (W87 JTA board using nano-connectors) or optical components (optical switch in a UC1530 communication module operating between 850- 900nm). Additionally, the historical data generated by the Airforce, Battelle, Bell Labs and NMSU Advanced Interconnection Laboratory demonstrate that 1) this material has no adverse interactions with a wide variety of plastics and metals, and 2) this material is beneficial towards reducing corrosion in connectors, including fretting corrosion in nano-connectors. Based on this data, I recommend that this material be qualified for use as a corrosion inhibitor and lubricant on WR nano-connectors.

Purpose of Study: To gain an understanding of the long-term aging and material compatibility characteristics of the lubricant (MIL-L-87177) so that we might recommend its qualification for WR use. To that end, we have developed a test plan that will answer the following questions:

- Will the lubricant ever migrate?
- Will the lubricant interfere with the functionality of the electrical connectors?
- Will the lubricant have any material compatibility issues with other systems? (i.e. getter material or optical switches)

Philosophy Behind Test-Plan: We are confident, because of the vast amount of data generated by the Airforce, Battelle and Bell Labs, that this material has no adverse interactions with a wide variety of plastics and metals. Consequently, this study will only include the lubricant, nanoconnectors, glass slides (to stand in for optical switches) and getter material (DEB).

Materials and parts will be thermal cycled in sealed canisters. Functional boards with nano-connectors, key questionable materials (i.e. DEB getter) and glass slides will be thermal cycled with and without the lubricant. After every 25 thermal cycles:

- The boards will be functionally tested.
- The gas in the canisters will be analyzed for trace lubricant and/or degradation products of the lubricant.
- Glass slides (duplicate samples) will be extracted with solvent and analyzed using mass spectroscopy to determine whether or not the lubricant will migrate and condense on other parts.
- DEB getter material will be analyzed to determine its ability to take up hydrogen.

Results: We have completed the 150th and final thermal cycle in this study. At 25 cycle intervals, a variety of tests were performed to monitor the functionality of the boards and connectors as well as to determine if the lubricant or any degradation product of the lubricant had migrated. Throughout this study, all the boards passed the electrical functional testing and continued to function properly. After the 100th cycle, the connectors in canisters 5 and 6 tested slightly high for contact resistance (15% increase). These high readings were attributed to an increase in ambient humidity (the humidity was at 50% —usually these measurements are taken at less than 40% humidity). After the next set of thermal cycles was completed (125th cycle), the contact resistance for these connectors had returned to normal (less than 0.4mV drop in voltage with constant 100mA current applied). Because contact resistance readings did return back to normal when tested at less than 40% humidity, we considered these connectors to be unaffected. They also tested normally after the 150th cycle was completed.

There has been no significant evidence of lubricant in the head-gas samples from the canisters. Additionally, throughout the study, there has been no significant amount of lubricant found on the glass slides.

DEB is a hydrogen getter that is placed throughout certain weapons for the purpose of trapping hydrogen (a gas that will embrittle metals such as stainless steel) that is produced by some systems. Upon completion of the 125th and 150th thermal cycle, samples of hydrogen getter were analyzed for its ability to take up hydrogen. Each sample of DEB was found to be very active which is typical for getters in particle form. The DEB seems to be unaffected by the presence of very small amounts of the MIL-L-87177 lubricant.

It was noted during this study that the lubricant, when taken directly from the can, is a clear yellow liquid. In order to acquire the thick samples that we desired for the optical study, we left some samples out to evaporate in the air. We found that the evaporated residue turned a dark blue color over the course of several days when left out in the air. We repeated the optical study using copious amounts of the blue lubricant residue applied onto the optical switch in a UC1530 communication module and found it to be transparent in the wavelength of interest (between 850 and 900nm). The fact that this product turns color when left out in the air should be noted, but not considered a problem in the context of our application. We will never allow large puddles of this material to stand on a component. For this study, a 6% solution of lubricant (as it came from the manufacturer) was applied using a paintbrush. For future work, we may want to refine the application technique as well as the percent concentration of lubricant in solution.

Acknowledgements: Thanks go out to Ron Taylor, Micky Clifford, Ed Fuller, Joe Laoruangroch, Anna Crabtree, Mike Conley, Charlie Cook and Charlie Long at Honeywell. Thank you Brian Geery (SNL-Org 2125) for working with us to collect the spectroscopic data on the UC1530. Thanks also go out to Jim Hanlon for his helpful consultations.

Test Matrix and Results

Cycle #	Electrical Functionality	Head-Space GC/MS on Gas in Canister	DEB Hydrogen Uptake	MS on Glass Slide Extract
25th	Passed all electrical tests--the boards continue to function properly.	No significant evidence of lubricant or constituents of lubricant in the canister gas.	Not Tested	Not Tested
50th	Passed all electrical tests--the boards continue to function properly.	No significant evidence of lubricant or constituents of lubricant in the canister gas.	Not Tested	Levels of lubricant were barely above background signal.
75th	Passed all electrical tests--the boards and connectors continue to function properly.	No significant evidence of lubricant or constituents of lubricant in the canister gas.	All samples easily passed acceptance criterion.	Not tested.
100th	Passed all electrical tests--the boards and connectors continue to function properly.	No significant evidence of lubricant or constituents of lubricant in the canister gas.	All samples easily passed acceptance criterion.	Levels of lubricant were background signal level.
125th	Passed all electrical tests--the boards and connectors continue to function properly.	No significant evidence of lubricant or constituents of lubricant in the canister gas.	All samples easily passed acceptance criterion.	Not tested.
150th	Passed all electrical tests--the boards and connectors continue to function properly.	No significant evidence of lubricant or constituents of lubricant in the canister gas.	All samples easily passed acceptance criterion.	Levels of lubricant were background signal level.

Test Matrix

Control 1	2 nano-connectors on test component (W87 JTA board), 10 glass slides stacked in a fixture so they aren't shadowing each other. 17 g DEB. Back-fill canister with dry nitrogen.	Nano-connectors unlubricated
Control 2	2 nano-connectors on test component (W87 JTA board), 10 glass slides stacked in a fixture so they aren't shadowing each other. 17 g DEB. Back-fill canister with dry nitrogen.	Nano-connectors unlubricated
3	2 nano-connectors on test component (W87 JTA board), 10 glass slides stacked in a fixture so they aren't shadowing each other. 17 g DEB. Back-fill canister with dry nitrogen.	Nano-connectors lubricated with ML-L-87177
4	2 nano-connectors on test component (W87 JTA board), 10 glass slides stacked in a fixture so they aren't shadowing each other. 17 g DEB. Back-fill canister with dry nitrogen.	Nano-connectors lubricated with ML-L-87177
5	1 connector (male/female), 10 glass slides stacked in a fixture so they aren't shadowing each other. 16 g DEB. Back-fill canister with dry nitrogen.	Amphenol Connector set: SA1529-5 &SA1530-5 lubricated with ML-L-87177
6	1 connector (male/female), 10 glass slides stacked in a fixture so they aren't shadowing each other. 16 g DEB. Back-fill canister with dry nitrogen.	Amphenol Connector set: SA1529-5 &SA1530-5 lubricated with ML-L-87177

Thermal cycle profile:

- Starting at room temperature (25^{o}C), ramp up to 71^{o}C using a 1^{o}C/min ramp-rate. Hold at 71^{o}C for 2 hours.
- From 71^{o}C, ramp down to –40^{o}C over the course of 2 hours (1^{o}C/min ramp-rate). Hold at –40^{o}C for 2 hours.
- From –40^{o}C, ramp up to 71^{o}C over the course of 2 hours (1^{o}C/min ramp-rate). Hold at 71^{o}C for 2 hours.
- Repeat steps 2 and 3 until 150 cycles have been completed.

Application of Lubricant
The lubricant was applied full strength (4% lubricant package diluted with 96% Freon) with a small paintbrush.

Electrical Functional Testing
The circuit board run in the Lubricant Material Compatibility tests is a W87 JTA, MITSI-12 VER.1 – 12-bit Multi-Channel Intelligent Time Division Sensor Interface. It contains a Nanonics (STM009P6SN) connector which was treated with MIL-87177 lubricant at a full concentration level as it was supplied by ILFC. The following functional tests were run on the MITSI-12 board to verify its continuing operation.

- DIGITAL TEST verifies the digital communications between the module and the tester.
- ACCELEROMETER TRANSFER provides data for the input-to-output transfer function of the accelerometer channel.
- TEMPERATURE TRANSFER provides data for the input-to output transfer function of the temperature channel.
- ACCELEROMETER AND TEMPERATURE CALIBRATION checks to see that the accelerometer and temperature data outputs are properly calibrated.

DEB-Hydrogen Getter: DEB is a hydrogen getter that is placed throughout the weapon for the purpose of trapping hydrogen that is produced by some systems. If hydrogen is allowed to linger next to metal surfaces, it will react with the metal and form a metal hydride, which will embrittle the metal and eventually cause cracks and failures.

Upon completion of the 75th and 100th thermal cycle, samples of hydrogen getter (75% 1,4-bis(phenylethylnyl)benzene (DEB) blended with 25% by weight palladium catalyst on carbon) was analyzed for its ability to take up hydrogen. The role of the catalyst in the hydrogen getter is crucial. It is known that certain chemicals can poison the catalyst and render the hydrogen getter ineffective. Since we have no materials compatibility information concerning how trace amounts of the lubricant might affect the catalyst in the DEB mixture, we have included the DEB getter package in our study.

Each sample of DEB was found to be very active which is typical for getters in particle form. The DEB was placed in a Parr bomb where it was evacuated to less than 1 mmHg and then backfilled with a known amount of hydrogen. The DEB was considered good if it took up 35% of the theoretical capacity within 4 hours. All samples easily met this criterion for acceptance.

Additional Spectroscopic Experiments - Effect of MIL-L-87177 Lubricant on the Optical Switch in a UC1530 Communication Module: In addition to the experiments outlined in the existing test matrix, we also had an opportunity to get direct results on how the lubricant would affect the output signal power in an optical switch. Specifically, we were able to apply the lubricant onto a polycarbonate window (such as that used in a UC1530 Communication Module) and measure the affect that copious coatings of the lubricant had on the signal output. The wavelength that the UC1530 communicates at is between 850 and 900nm. The transmitter output intensity was 330 milliwatts/steradian (mW/Sr). The path length in this experiment was 36.8 cm. With just air in the path length, the signal was 100%. With the clean polycarbonate window in front of the receiver, we saw a 6% drop in signal. Several coats of lubricant (visible to the eye) applied to the polycarbonate window did not affect the signal intensity. It was not until we applied an extremely heavy amount of lubricant that we saw about a 3-4% drop in signal. This amount of signal drop will have no significant effect on the functionality of this optical switch. For a switch of this type to fail, there would have to be a drop in signal power of over 50 percent.

References:

1. G. De Marquis, "Progress Report: Qualification of MIL-L087177 for Use as a Corrosion Inhibitor and Lubricant of WR Nano-connectors." April 24, 2001.

2. G. De Marquis, "Progress Report: Qualification of MIL-L087177 for Use as a Corrosion Inhibitor and Lubricant of WR Nano-connectors." February 20, 2001.

3. George Kitchen, "The Evolution of a Water Displacing Corrosion Preventative Lubricant" NACE (National Association of Corrosion Engineers) conference, April 2000.

4. W. H. (Bill) Abbott, "Corrosion Monitoring of Air Force Field Sites and Effects of Lubrication on Corrosion Inhibition" NACE conference, April 2000.

5. David H. Horne, USAF F-16 Fuel Systems Engine, "Catastrophic Uncommanded Closures of Engine Feedline Fuel Valve from Corroded Electrical Connectors" NACE conference, April 2000.

6. Neil Aukland of The NMSU Advanced Interconnection Laboratory and James Hanlon of Sandia National Laboratories, "MIL-L-87177 and a Commercial Lubricant Improve Electrical Connector Fretting Corrosion Behavior." NACE conference, April 2000.

7. Bill Abbott at Battelle, "Evaluation of Lubricant Effectiveness for Corrosion Protection and Improved Reliability of Electrical and Electronic Connectors" Final Report to Hill Air Force Base, Contract No. F04606-89-D-0034-RZ05, August 28, 1996.

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Appendix L

Bryan Balazs, "Assessment of compatibility issues associated with the use of electrical connector lubricant MIL-L-87177A"
(3 pages)

University of California
Lawrence Livermore National Laboratory

Weapon Materials Compatibility and Aging Group
Chemistry and Chemical Engineering Division
Chemistry & Materials Science Directorate

MEMORANDUM: September 11, 2000

TO: Distribution

FROM: G. Bryan Balazs

SUBJECT: **Assessment of compatibility issues associated with the use of electrical connector lubricant MIL-L-87177A**

Summary

We have been asked to provide an assessment of any negative compatibility issues that could arise as a result of the use of the electrical connector lubricant MIL-L-87177A in the non-nuclear section of various DOE systems. This lubricant would typically be applied very sparingly to micropin connectors during assembly, and traces of the material would remain on the connector and thus be captured in the weapon's internal atmosphere for its lifetime. Our assessment is based on an analysis of the chemical constituents of the lubricant and on accumulated expertise in scenarios such as this one. We foresee no detrimental compatibility issues, although it is suggested that a rigorous set of compatibility tests involving this lubricant system with appropriate materials would increase the confidence that there are no negative issues associated with the use of this lubricant. We make this assessment without reference to specific materials found in specific weapon systems (with the exception of a getter discussed below), but rather from a general compatibility standpoint relevant to organic species commonly found on LLNL systems.

Composition of the lubricant

The constituent materials of MIL-L-87177A lubricant have been provided to SNL by International Lubrication and Fuel Consultants, but they are proprietary to the company and we will not list them in this report. If you need to know more about the composition of the lubricant, please contact one one of the authors.

Compatibility Assessment

Of these materials comprising this formulation, the majority (by weight) are diluents for the actual lubricant. However, experience with organic chemicals and weapon systems in general has shown that virtually all materials used in conjunction with assembling a weapon can be found in the system's internal atmosphere (oftentimes in only trace quantities). It should be noted at this point that the intended usage for this lubricant formulation calls for only minute quantities to be applied, and thus it is not expected that there will be significant quantities of any of the chemical components to begin with. Typical applications might be on the order of milligrams, with the majority of this quantity being the carrier Freon.

Freons are relatively volatile and thus would likely be vaporized shortly after application, although trace quantities would likely be sealed up in the weapon internal atmosphere. It is not believed that any negative compatibility issues would arise with this material, especially given the extremely low concentrations likely to exist. The lubricant oil itself, poly 1-decene, is highly nonvolatile and thus would not be expected to migrate substantially. The other materials (additives and stabilizers) are either solids or relatively nonvolatile liquids, again in trace quantities. No general problems can be foreseen with these additives, but we do raise a note of caution for some of them in conjunction with the hydrogen getter DEB. This hydrogen getter (in powder form) consists of 75 wt% of 1,4-bis(phenylethynyl)benzene (DEB) blended with 25 wt% of a carbon-supported Pd catalyst; this catalyst is in turn 5% palladium and 95% activated carbon. The role of the catalyst is crucial, and it is known that certain chemicals can poison the catalyst and render the getter ineffective. For example, carbon monoxide is a poison[2], and there are other potential poisons with amines and sulfur compounds. Thus, some caution is raised by the last two components in the formulation list above. Again, given the low volatility and extremely small quantities of these species, it is unlikely that they would have a detrimental effect on the getter unless inadvertently placed in direct contact with each other. It is suggested that specific individuals more familiar with getter poisons[3] be contacted for further information.

REFERENCES

[1] from an email from Ginger De Marquis (SNL-NM) to Bryan Balazs, July 31, 2000.
[2] from an email from Jim Schicker (Honeywell FMT) to Bryan Balazs, August 4, 2000.
[3] E.g., Gene Mroz (LANL)

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Appendix M

MIL-L-87177A, February 9, 1990.
(18 pages)

INCH–POUND

MIL–L–87177A
9 February 1990
SUPERSEDING
MIL–L–87177
9 September 1983

MILITARY SPECIFICATION

LUBRICANTS, WATER DISPLACING, SYNTHETIC

This specification is approved for use by all Departments and Agencies of the Department of Defense.

1. SCOPE

1.1 Scope. This specification covers synthetic, water displacing lubricant, compounds which may be applied from gas pressurized containers, or by dipping or brushing.

1.2 Classification. The compound shall be furnished in the specified types and grades (see 6.2).

1.2.1 Types. The compound types shall consist of the following:

a. Type I: Pressurized spray container (for spray application).

b. Type II: Bulk form.

1.2.2 Grades. The compound grades shall be designated as follows:

a. Grade A: Lubricant, water displacing, synthetic.

b. Grade B: Lubricant, water displacing, synthetic, with added corrosion inhibitor.

c. Grade C: Lubricant, dry spray, synthetic.

2.1 Government documents

2.1.1 Specifications and standards. The following specifications and standards form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DODISS) and supplement thereto, cited in the solicitation (see 6.2)

Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: ASD/ENES, Wright–Patterson AFB OH 45433–6503 by using the self–addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

AMSC N/A FSC 9150

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

2. APPLICABLE DOCUMENTS

SPECIFICATIONS

FEDERAL

A–A–51126	Anodes, Cadmium
QQ–A–250/4	Aluminum Alloy 2024, Plate and Sheet
QQ–B–626	Brass, Leaded and Nonleaded Rod, Shapes,Forgings and Flat Product TH Finished Edges(Bar and Strip)
QQ–C–576	Copper Flat Products with Slit, Slit and Edge–Rolled, Sheared, Sawed or Machined Edges, (Plate, Bar, Sheet, and Strip)
QQ–M–44	Magnesium Alloy Plate and Sheet (AZ31b)
TT–N–95	Naphtha, Aliphatic
TT–T–291	Thinner, Paint, Mineral Spirits, Regular and odorless
MMM–A–250	Adhesive, Water–Resistant (For Closure of Fiberboard Boxes)
PPP–B–636	Box, Shipping, Fireboard
PPP–C–96	Can, Metal, 28 Gage and Lighter

MILITARY

MIL–S–7952	Steel, Sheet and Strip, Uncoated, Carbon (1020 and 1025) (Aircraft Quality)
MIL–A–18001	Anode, Corrosion Preventative, Zinc, Slab Disc and Rod Shaped
MIL–S–22805	Spray Kit, Self Pressurized

STANDARD

FEDERAL

FED–STD–313	Material Safety Data Sheets Preparation and the Submission of

MILITARY

MIL–STD–105	Sampling Procedures and Tables for Inspection by Attributes
MIL–STD–290	Packing of Petroleum and Related Products

(Unless otherwise indicated, copies of federal and military specifications and standards are available from the Naval Publications and Forms Center, (ATTN: NPODS), 5801 Tabor Avenue, Philadelphia, PA 19120–5099.)

2.2 Non–Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DODISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DODISS are cited in the solicitation (see 6.2)

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

ASTM B 117	Method of Salt Spray (Fog) Testing (DoD adopted)
ASTM D 740	Methyl Ethyl Ketone
ASTM D 877	Dielectric Breakdown Voltage of Insulating Liquids Using Disk Electrodes (DoD adopted)
ASTM D 942	Oxidation Stability of Lubricating Greases by the Oxygen Bomb Method (DoD adopted)
ASTM D 1310	Flash Point of Liquids by Tag Open–Cup Apparatus (DoD adopted)
ASTM D 2266	Wear Preventive Characteristics of Lubricating Grease (Four–Ball Method) (DoD adopted)

(Applications for copies should be addressed to American Society for Testing and Materials, 1916 Race Street, Philadephia, PA 19103–1137.)

DEPARTMENT OF TRANSPORTATION

29 CFR 1910.2100 Material Safety Data Sheet, Preparation and Submission of

49 CFR 173.300 Department of Transportation Hazardous Materials Regulation

(Application for copies should be addressed to Department of Transportation, 400 7th Street, SW, Washington, DC 20590.)

(Non–Government standards and other publications are normally available from the organizations that prepare or distribute the documents. These documents also may be available in or through libraries or other informational services.)

2.3 Order of precedence. In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specified exemption has been obtained.

3. REQUIREMENTS

3.1 First article. When specified (see 6.2.2.1), a sample shall be subjected to first article inspection in accordance with 4.4.

3.2 Material safety data sheet. Material safety data sheets shall be prepared in accordance with FED–STD–313 and 29 CFR 1910.2100. When FED–STD–313 is at variance with the CPR, 29 CFR 1910.2100 shall take precedence, modify and supplement FED–STD–313.

3.3 Properties. The compound shall conform to the properties specified in table I.

3.3.1 Type I compound. The type I compound (See table I) shall be contained in a gas pressurized container with a 80 percent volume of the compound and 2.7 percent volume of carbon dioxide.

3.3.2 Type II compound. The type II compound (see table I) shall be in bulk form.

3.3.3 Type packaging

3.3.3.1 Packaging of compound in gas pressurized containers. The pressurized containers shall hold 16 ounces. The containers shall conform to class 2, type IX of PPP–C–96 with a valve opening diameter suitable for the specified valve.

3.3.3.2 Nonpressurized containers. Nonpressurized packaging of the compound shall be in containers conforming to PPP–C–96, type VIII.

3.4 Performance

3.4.1 Type I – pressurized container. The pressurized container shall meet requirements specified herein and shall meet Department of Transportation requirements.

3.4.1.1 Leakage. The pressurized container shall not leak or become distorted when tested as specified in section

3.4.1.2 Content. The pressurized containers shall contain a minimum of 16 ounces when tested as specified in section

3.4.1.3 Performance of compound. The compound packaged in the pressurized containers shall spray uniformly, adhere to the panel, and shall not foam excessively or sag when tested as specified in section 4.

3.4.2 Type II – bulk form. When tested as specified as applicable in section 4, the compound shall meet the properties of table I.

3.4.3 Corrosivity. Grade A compound shall show no evidence of corrosivity as specified in table I when tested as specified in section 4.

3.4.4 Corrosion resistance. Grade B compound shall show no evidence of corrosion as specified in table I when tested as specified in section 4.

3.4.5 Toxicity. The compound shall have no adverse effect on the health of personnel when used for its intended purpose . Questions pertinent to this effect shall be referred by the contracting activity to the appropriate departmental medical service who will act as an advisor to the contracting agency.

3.5 Workmanship. The compound shall be homogeneous, free from grit, abrasives, water, inorganic chlorides and other impurities. A typical formulation is given in table I. The exterior orifice of the pressurized containers shall be symmetrical and free of ragged edges, and the exterior orifice, if drilled, shall be symmetrical and in direct alignment with angle of discharge.

4.1 Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the contractor is responsible for the performance of all inspection requirements (examinations and tests) as specified herein. Except as otherwise specified in the contract or purchase order, the contractor may use his own or any other facilities suitable for the performance of the inspection requirements specified herein, unless disapproved by the Government. The Government reserves the right to perform any of the inspections set forth in the specification where such inspections are deemed necessary to assure supplies and services conform to prescribed requirements.

TABLE I. Physical and chemical properties.

Characteristics	Limits
Dryness	0.0100 gram (max)
Flash point	243°C(470°F)(min)
Grade A Synthetic sea water displacement	No visible corrosion. Fine localized pitting shall not be cause for rejection
Dielectric breakdown	25,000 volts (min)
Lubricity	1.20 mm wear scar diameter (max)
Residue soluble trichlorotrifluoroethane	No visible residue
Oxidation stability	Less than 5 pounds per 100 hours
Grade A corrosivity	No visible pitting, etching, or dark discoloration. No weight change (milligrams/ cm^2) greater than 0.5 for magnesium, cadmium and zinc; nor greater than 0.2 for aluminum, copper and brass.
Grade B corrosion	No evidence of corrosion on the resistance base metal when exposed for 168 hours in accordance with methods specified in section 4.
Sprayability	Sprayable.

Grade C shall meet all the physical and chemical properties in table I except the corrosivity (Grade A) and corrosion resistance (Grade B) requirements.

4. QUALITY ASSURANCE PROVISIONS

4.1.1 Responsibility for compliance. All items shall meet all requirements of sections 3 and 5. The inspection set forth in this specification shall become a part of the contractor's overall inspection system or quality program. The absence of any inspection requirements in the specification shall not relieve the contractor of the responsibility of ensuring that all products or supplies submitted to the Government for acceptance comply with all requirements of the contract. Sampling inspections, as part of manufacturing operations, is an acceptance practice to ascertain conformance to requirements, however, this does not authorize submission of known defective material, either indicated or actual, nor does it commit the Government to accept defective material.

4.2 Classification of inspections. The inspection requirements specified herein are classified as follows:

a. First article inspection (4.4)

b. Quality conformance inspection (4.5).

4.3 Inspection conditions

4.3.1 Test conditions. In general, physical tests contained in this specification shall be made under controlled atmospheric conditions having a relative humidity of 50 + 5 percent and a temperature range of from 21 C to 27°C (70°F to 80°F). Waiver of this requirement may be permitted where proper conditioning facilities are not available for control testing. However, for referee purposes, the specified tests shall be made upon the compound under the specified atmospheric conditions.

4.3.2 Specimen for test

4.3.2.1 Materials. The material for the test disks and panels shall be carbon steel conforming to composition 1020 of MIL–S–7952.

4.3.2.2 Size of test disk and panels. Test panels for tests requiring compound coatings shall be 2 by 4 by 1/8 inches; the dryness tests shall require disks with a diameter of 2–1/8 inches and a thickness of 1/16 inch.

4.3.2.3 Preparation of test panels (or disks). Panels (or disks) shall have all sharp edges and burrs removed and shall have all holes chamfered to prevent injury in handling. The panels (or disks) shall be surface ground and hand polish with a 240 grit silicon carbide or aluminum oxide cloth or paper to produce a surface finish of 10 to 20 microinches (rms). Iron oxide or so–called "wet or dry" papers or cloths shall not be used.

4.3.2.4 Cleaning test panels (or disks). The utensils and cloths used in the cleaning of test panels (or disks) shall be clean and free of contamination. Solvents shall be fresh and renewed frequently. In all stages of treatment the handling of panels (or disks) with the bare hands shall be avoided. The panels (or disks) shall not be permitted to contact contaminated surfaces during the cleaning procedure and shall be handled by tongs and hooks during and after dipping. After polishing, they shall be cleaned with a surgical gauze swab, in a beaker of hot mineral spirits conforming to type I of TT–T–291. Cleaning and scrubbing shall be followed by dipping in (1) a second container of hot mineral spirits, (2) boiling 95 percent methanol, and (3) boiling absolute methanol. The panels (or disks) shall be allowed to dry and shall then be stored in a desiccator until ready for use. If storage of more than 24 hours occurs, the surface preparation shall be repeated starting with the hand polishing.

4.3.2.5 Coating of the test panels (or disks). Application of the compound to the test panels (or disks) shall be carried out under the atmospheric conditions of 4.3.1. The panels (or disks) shall be held at an angle of 30 degrees from the horizontal. A coating of the compound shall be sprayed on the panels (or disks) from a pressurized container or a container conforming to MIL–S–22805 held 12 inches away. After ten minutes, a second coating shall be sprayed on. The combined thickness of the two coats after drying shall be 1.2 to 1.5 mils. After application they shall be conditioned for 24 hours under the atmospheric conditions of 4.3.1 in a draft–, dust– and fume– free atmosphere.

4.3.3 Inspection lot. An inspection lot shall consist of all material produced during a single batch operation and offered for acceptance at one time.

4.4 First article inspection

4.4.1 Waiver of article sample inspection. If a contractor has previously furnished the compound in accordance with the requirements of this specification and his product has been found to be satisfactory, the requirement for a first article sample and its submittal for any subsequent contract or order may be waived at the discretion of the procuring activity.

4.4.2 First article samples. First article sample shall consist of at least five type I filled pressurized containers (see 3.3.1), or 5 quarts of the type II compound (see 3.3.2). Samples shall be selected at random from materials (see 3.1) which have been manufactured or used for filling the contract.

4.4.2.1 Identification of samples. Samples shall be plainly identified by securely attached durable tags marked with the following information:

LUBRICANT, CORROSION PREVENTIVE COMPOUND, WATER
DISPLACING, SYNTHETIC GRADE _______
Samples of material subjected to first article
Name of Manufacturer (Plant in which material is manufactured)
Manufacturer's Designation
Date of Manufacture
Submitted by (Name) (Date) for Contract No. _________

The manufacturer shall submit a copy of test results with the samples showing conformance with all the requirements of this specification and the applicable requirements of regulation 49 CFR 173.300 of the Department of Transportation. The manufacturer shall submit a certified statement specifically identifying each ingredient in the compound by chemical name, source and percentage by weight.

4.4.3 First article tests. First article sample(s) shall be subjected to all the tests specified in table II to determine compliance with the requirements of section 3 herein.

4.5 Quality conformance inspection. Samples shall be labeled completely with information identifying the purpose of the sample, name of product, specification number, lot and batch number, date of sampling and contract number.

4.5.1 Sampling plan A. One type I filled pressurized container (see 3.3.1) and one quart of the type II compound (see 3.3.2) shall be selected in accordance with MIL–STD–105, inspection level S–3 with an AQL 4.0 percent defective and shall be subjected to the tests specified in table III.

TABLE II. First article testing 1/

Characteristics	Requirements	Test method	ASTM
Dryness	3.3, table I	4.6.1	
Flash point	3.3, table I		D1310
Grade A synthetic sea water displacement	3.3, table I	4.6.2	
Dielectric breakdown	3.3, table I		D877
Lubricity	3.3, table I		D2266 2/
Residue soluble in trichlorotrifluoroethane	3.3, table I	4.6.3	
Leakage	3.4.1.1	4.6.4	
Content	3.4.1.2	4.6.5	
Performance of pressurized containers	3.4.1.2	4.6.6	
Oxidation stability	3.3, table I		D942
Grade A corrosivity	3.4.3	4.6.7	
Grade B corrosion resistance	3.4.4	4.6.8	
Sprayability	3.3, table I	4.6.9	

Grade C shall meet all the first article testing in table II, except the corrosivity (Grade A) and corrosion resistance (Grade B) requirements.

1/ Refer to 4.3.1

2/ Compound shall be weathered before loading into ball pot.

4.5.2 Sampling Plan B. A random sample of type I filled containers shall be selected in accordance with MIL–STD–105, inspection level I with an AQL 2.5 percent defective from each inspection lot (see 4.3.3). The sample container(s) shall be subjected to the tests specified in table II.

4.5.3 Certification. The manufacturer shall certify that there has been no formulation or process change from that which resulted in the production of the first article inspection sample(see 4.4.2). Each ingredient material shall be identified with the name of its manufacturer and that manufacturer's trade name and formula number.

TABLE III. Quality conformance inspection 1/

Inspection	Requirement paragraph	Test paragraph
Grade A Corrosivity	3.4.3	4.4, 4.5 4.6, 4.6.7
Grade B Corrosion resistance	3.4.4	4.4, 4.5 4.6, 4.6.8
Leakage	3.4.1.1	4.6.4
Contents	3.4.1.2	4.6.5
Performance of pressurized containers	3.4.1.3	4.6.6

1/ Refer to 4.5.

4.5.4 Inspection of packaged containers. The packaging containers, packing, and marking of type I and type II compound shall be inspected to determine conformance to the requirements of section 5. Selection shall be in accordance with MIL–STD–105, inspection level S–2, 2.5 percent defects per 100 units. Sample units used in sampling plans A and B shall be used for this inspection (see 4.4.2).

4.6 Method of inspection

4.6.1 Dryness test. Three test disks (4.3.2.2) prepared as specified in 4.3.2.3 shall be cleaned as specified in 4.3.2.4, coated as in 4.3.2.5, and allowed to hang in a vertical position for two hours. They shall then be weighed and completely immersed vertically in talcum powder and withdrawn immediately. They shall then be reweighed to the nearest 0.0001 gram. The average change in weight shall be recorded. This procedure shall be repeated with test disks which have not been coated. These shall be used as controls. The average weight increase of the coated panels as compared with the weight increase of the uncoated panels shall be the measure of dryness.

4.6.2 Grade A– synthetic sea water displacement procedure. Panels prepared as specified in 4.3.2.3 and 4.3.2.4 shall be so placed that one 2–inch end shall be raised one inch above a horizontal surface. The panels shall then be sprayed with the synthetic sea water so that the entire upper surface of specimen is covered with tiny droplets. Within one minute after spraying, one milliliter of the test compound shall be poured along the upper 2–inch edge of the panels and allowed to run slowly down the specimen so as to completely cover the test panel. After another minute, a second milliliter of the test compound shall be poured and allowed to run down the panels in a like manner. After waiting an additional minute, the panels shall be picked up and held in a vertical position for one minute and shall then be placed flat (test side up) above distilled water at 7°F in a closed desiccator. After 24 hours they shall be removed and cleaned with mineral spirits, and then evaluated for presence of visible corrosion.

4.6.3 Determination of solubility in Freon TF. At least three dip clean coated test panels shall be dipped in boiling 95 percent methanol and let stand for one hour. After one hour, the test panels shall be rinsed twice with fresh Freon TF and examined visually. There shall be no visible residue on panels.

4.6.4 Leakage test. The pressurized container shall be completely submerged for five minutes in water maintained at 130°F + 2°F during which it shall be observed for the emission of bubbles. Distortion of the container or the emission of bubbles from any part of the container shall be considered evidence of leakage.

4.6.5 Determination of container weight. A sample container shall be weighed and then shall be sprayed at three minute periods with one–minute intervals until the container is exhausted. The container shall be re–weighted. The net difference shall be at least 16 ounces by weight.

4.6.6 Performance of pressurized containers. Panels as described in 4.6.1 shall be used. A panel shall be supported such that the longer dimension forms a 45 degree angle with the horizontal. Type I packaged in accordance with 5.2.1 shall be sprayed on the panel from a distance of 12 inches. The panel shall be examined for uniformity of spray, foaming, and adherence to the substrate. After a 10 second pause the same panel shall be resprayed and examined for adhesion and sagging. After a 5 second pause the same panel shall be resprayed again and likewise examined.

4.6.7 Grade A – corrosivity test

4.6.7.1 Specimen preparations

4.6.7.1.1 Specimens of the following metals shall be used in this test:

Magnesium, QQ–M–44
Cadmium, A–A–51126
Zinc, MIL–A–18001
Aluminum, QQ–A–250/4
Copper, QQ–C–576
Brass, QQ–B–626

NOTE: Suggested specimen size is 3 x 1/2 x 1/16 inches.

4.6.7.1.2 Specimen procedure. Three specimens of each of the above metals shall be polished to remove pits, burrs, and irregularities from all faces and edges. The panels shall be finished and cleaned as specified in 4.3.2.3 and 4.3.2.4.

4.6.7.2 Test procedure. After weighing, the specimens shall be coated as specified in 4.3.2.5. After a one hour drying period the specimens shall be placed in a humidity chamber maintained at 130°F +2°F and 75 percent relative humidity for seven days (168 hours). Upon completion the coating and any loose corrosion products shall be removed by cleaning in acetone. Reweigh the specimens and calculate the weight loss or gain in milligrams per square centimeter. The specimens shall meet the requirements of 3.4.3.

4.6.8 Grade B – corrosion resistance test. The corrosion resistance test shall be conducted in accordance with the procedure specified in ASTM B 117 to determine conformance with 3.4.4.

4.6.9 Sprayability (in pressurized container) test. A filled pressurized container shall be cooled to 0°F held at that temperature for 3 hours, and then stored at 40°F for 20 hours. Immediately after conditioning, the container shall be shaken vigorously for 15 seconds and the material sprayed for 30 seconds. The material shall be considered as having passed the test if it can be satisfactorily sprayed.

5. PACKAGING

5.1 Packaging. Packaging shall be Level A or C in accordance with MIL–STD–290 as specified in the contract or order. Neither the container, nor any component thereof (closure, lining, etc.), shall interact with or alter the contents in any way so as to adversely affect their purity or quality. All containers shall be new and free from contaminants.

5.2 Packing. Except as specified in 5.2.1 packing shall be Level A, B, or C in accordance with MIL–STD–290 as specified in the contract or order (see 6.2).

5.2.1 Packing of filled pressurized containers

5.2.1.1 Level A. Twenty–four dispensers shall be packed in a fiberboard box conforming to PPP–B–636, Style F.O.L., compliance symbol V3s or V3c. The twenty– four dispensers shall be arranged: six in length, four in width and one in depth, and shall be separated by slotted partitions providing an individual cell for each dispenser. Partitions shall be B or C flute, double faced corrugated board. Box liners of the same material as the partitions shall be provided. The corrugations of the liners shall run vertically. Liners shall be cut so that on placement the ends abut in the middle of one side of the box. Box and all components shall be fabricated of material having not less than 200 pounds per square inch bursting strength.

5.2.1.1.1 Level A closure. All flaps of the box shall be securely sealed with a water–resistant adhesive conforming to MMM–A–250. The adhesive shall be applied throughout the entire area of contact between the flaps.

5.2.1.2 Level B. Twenty–four dispensers shall be packed in a domestic type corrugated or solid fiberboard container. Style F.O.L. (less 1 inch) conforming to PPP–B–636. Arrangement shall be: six in length, four in width, and one in depth. Slotted partitions shall be employed to form an individual cell for each dispenser. Partitions shall be B or C Flute, double faced corrugated board. Box liners of the same material as the partitions shall be provided. The corrugations of the liners shall run vertically. Liners shall be cut so that on placement the ends abut in the middle of one side of the box. Box and all components shall be fabricated of material having not less than 200 pounds per square inch bursting strength. All flaps shall be sealed with a good quality adhesive applied throughout the entire area of contact between flaps.

5.2.1.2.1 Strapping. Strapping shall be in accordance with the appendix of PPP– B–636.

5.3 Marking. Marking of the containers shall be in accordance with MIL–STD–290, except as specified herein. Marking shall be legible, shall be accomplished by lithographing or silkscreen process and shall be white on an orange label or as specified in the contract. Paper coated labels on pressurized containers are not acceptable; any special marking specified in the contract or order shall also be included. In addition, the following information shall be included on each gas pressurized container and bulk container as applicable (when not already required by MIL–STD–290 or the contract or order):

Front Face:

(Stock No.)
LUBRICANT, WATER DISPLACING, SYNTHETIC GRADE _______
MIL–L LOT ________ DATE MFG ________
CONTRACT NO.)
MANUFACTURER'S NAME)
(MANUFACTURER'S ADDRESS)
(MANUFACTURER'S PRODUCT NO.)
CONTAINER SIZE BY VOLUME

IMPORTANT! For best results follow instructions on reverse side of container.

USES

This material will displace salt water and moisture leaving a corrosion preventive film. It is intended for use on areas which are unpainted metal, where the paint has cracked or been damaged such as: around fasteners, seams, access panels, etc. It is intended for use on moving parts which require a lubricated surface.

Instructions – for best results

I. Wipe off dirt and excess moisture from surface to be protected prior to applying the corrosion preventive compound.

2. Apply a thin uniform coat of corrosion preventive compound directly on area to be protected.

3. Allow to dry for one half hour.

4. Apply a second uniform coat of corrosion preventive compound.

5. Application by wiping is not recommended. Reapplication of compound is necessary after solvent cleaning or where coating has been damaged by abrasion.

NOTE: May be removed with methyl ethyl ketone
ASTM D 740 or aliphatic naptha TT–N–95.

CAUTION (for spray containers)

Contents pressurized. Do not puncture, incinerate, or store above 120° F. Do not place can near open flame or other heat source. Use with adequate ventilation and avoid breathing vapor.

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Intended use. The compounds covered by this specification may be used on any metal surfaces. They are primarily intended for in–service treatment of moving parts. The ability of these materials to lubricate, to prevent corrosion, to displace water and to be used at temperatures up to 20°C (40°F) make these particularly suited for service use. The temperature durability is a particular advantage of this material.

6.2 Ordering data. Requests, requisitions, schedules, and contracts or orders should specify the following:

a. Title, number, and date of this specification.

b. Grade and type.

c. Quantity. (Specify number of containers.)

d. Packaging desired (see 5.1)

e. Level of packing required (see 5.2)

f. Labeling or other special marking required (see 5.3)

6.2.1 Completed material safety data sheets. Contracting officers will identify those activities requiring copies of completed material safety data sheets prepared in accordance with 3.2. The pertinent government mailing addresses for submission of data are listed in appendix B of FED–STD–313.

6.2.2 Contract provision. Contracts shall specify the following provision for first article inspection.

6.2.2.1 First article. When a first article is required for inspection and approval (see 3.1, 4.4, and 6.2), the contract shall specify the following provision for first article inspection. When a contractor is in continuous production of the compound from contract to contract, consideration should be given to waive the first article inspections. If inspection is required, indicate:

a. If first article inspections are conducted at the contractor's plant or a government approved laboratory, an inspection report shall be forwarded to the procuring activity for certification.

b. That the approval of first article samples or the waiving of the first article inspection shall not relieve the contractor of his obligation to fulfill all other requirements of the specification and contract.

6.3 Typical formulation of compound for Grade A & B. A typical formulation is given in table IV. Grade B is intended for applications where severe corrosion is possible. Both Grade A and B can be used for control of surface static electricity and as a barrier film to minimize surface contamination.

6.3.1 Ingredients. The ingredients of table IV which, when properly processed, have produced a compound meeting the requirements of this specification for Grade A. The list of approved proprietary raw materials is not to be construed as an endorsement thereof or as precluding similar materials from other proprietary sources. Such products may prove equivalent or even superior in performance to the ones listed.

6.4 Samples. Samples shall be furnished at no cost to the Government, and the manufacturer shall pay the transportation charges to and from the designated point where tests are to be made. In the case of failure of the sample or samples submitted, considerations will be given to the request of the manufacturer for additional test only after it has been clearly shown that changes have been made in the product which the Government considers sufficient to warrant additional tests, and a new designation is given the material by the manufacturer.

TABLE IV. Grade A typical formulation.

Parts by Weight	Component Description (Formula) (Proprietary Name or Trade Name)	Supplier
96.61	Freon TF	E.I. DuPont De Nemours and Company (Inc) Wilmington DE 19898
2.36	Selig 1121 (A proprietary mixture registered with Environmental Health and Safety Department)	Selig Chemical Industries Atlanta GA 30336
1.03	Poly Alpha Olefin (6 centistokes at 99°C [210°F])	Gulf Oil Corporation Pittsburgh PA 15219

NOTE: Grade B has proprietary corrosion inhibiting compound added.

6.5 Heat testing of metal containers. Section 173.306 of the Department of Transportation Regulations specifies that each completed metal container filled for shipment must be heated until the contents reaches a minimum temperature of 130oF without evidence of leakage, distortion, or other defects.

6.6 Subject term (key word) listing

Synthetic sea water
Gas pressurized containers
Compound

6.7 Changes from previous issue. Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extensiveness of the changes.

Custodians:

Army – CR
Navy – AS
Air Force – II

Preparing activity:

Air Force – 11
(Project No. 9150–1033)

Review activities:
Air Force – 68

User Activities:
Army – AR
Navy – EC

INCH–POUND

MIL–L–87177A
AMENDMENT 1
28 February 1991

MILITARY SPECIFICATION

LUBRICANTS, WATER DISPLACING, SYNTHETIC

This amendment forms a part of MIL–L–87177A dated 9 February 1990, and is approved for use by all Departments and Agencies of the Department of Defense.

PAGE 1

Title: Delete and substitute "LUBRICANTS, CORROSION PREVENTIVE COMPOUND, WATER DISPLACING, SYNTHETIC"

1.1: Delete and substitute "1.1 Scope. This specification covers a synthetic, lubricant, water displacing corrosion preventive compound which may be applied from gas pressurized containers, or by dipping or brushing."

1.2.2a: Delete.

PAGE 2

2.1.1, under FEDERAL: Delete "A–A–51126, QQ–A–250/4, QQ–B–626, QQ–C–576, QQ–M–44, MIL–A–18001."

PAGE 3

Lines 1, 2 and 3: Delete and substitute "Unless otherwise indicated, copies of federal and military specifications and standards are available from the Standardization Documents Order Desk, Bldg 4D 700 Robbins Avenue Philadelphia PA 19111–5094."

PAGE 4

3.4.1.1 and 3.4.1.2, lines 2, after section: Add "4."

3.4.3: Delete.

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PAGE 5

Table I: Delete and substitute.

TABLE I. Physical and chemical properties.

Characteristics	Limits
Dryness	0.0100 gram (max)
Flash point	243°C(470°F)(min)
Dielectric breakdown	25,000 volts (min)
Lubricity	1.20 mm wear scar diameter (max)
Residue soluble trichlorotrifluoroethane	No visible residue
Oxidation stability	Less than 5 pounds per 100 hrs
Grade B corrosion	No evidence of corrosion on the resistance base metal when exposed for 168 hours in accordance with methods s specified in section 4.
Sprayability	Sprayable.

Grade C shall meet all the physical and chemical properties in table I except the corrosion resistance (Grade B) requirements.

PAGE 8

Table II: Delete and substitute.

TABLE II. First article testing 1/

Characteristics	Requirements	Test method	ASTM
Dryness	3.3, table I	4.6.1	
Flash point	3.3, table I		D1310
Dielectric breakdown	3.3, table I		D877
Lubricity	3.3, table I		D2266 2/
Residue soluble in trichlorotrifluoroethane	3.3, table I	4.6.3	
Leakage	3.4.1.1	4.6.4	
Content	3.4.1.2	4.6.5	
Performance of pressurized containers	3.4.1.2	4.6.6	
Oxidation stability	3.3, table I		D942
Grade B corrosion resistance	3.4.4	4.6.8	
Sprayability	3.3, table I	4.6.9	
Grade C shall meet all the first article testing in table II, except the corrosion resistance (Grade B) requirements.			

1/ Refer to 4.3.1

2/ Compound shall be weathered before loading into ball pot.

PAGE 9

Table III, lines 3 and 4: Delete "Grade A Corrosivity 3.4.3 4.4, 4.5, 4.6, 4.6.7".

4.6.2: Delete.

PAGE 10

4.6.7, 4.6.7.1, 4.6.7.1.1, 4.6.7.1.2, 4.6.7.2: Delete.

PAGE 12

Line 3, from top of page, delete and substitute: "LUBRICANTS, CORROSION PREVENTIVE COMPOUND, WATER DISPLACING, SYNTHETIC GRADE ____".

PAGE 13

6.3: Delete and substitute "Typical formulation of compound for Grade B. Grade B is intended for applications where severe corrosion is possible. Grade B can be used for control of surface static electricity and as a barrier film to minimize surface contamination".

6.3.1: Delete.

PAGE 14

Table IV: Delete.

Custodians:
Army – ME
Navy – AS
Air Force – 11

Preparing activity:
Air Force – 11

Review activities:
Air Force – 68
DLA – GS

Proj No. 9150–1078

User activities:
Army – AR
Navy – EC

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