MIL-L-87177 AND CLT:X-10 LUBRICANTS IMPROVE ELECTRICAL CONNECTOR FRETTING CORROSION BEHAVIOR

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

Dr. Neil R. Aukland
The Advanced Interconnection Laboratory
New Mexico State University
PO Box 30001, MSC 3450
Las Cruces, NM 88003

ABSTRACT

We have conducted a fretting research project using MIL-L-87177 and CLT: X-10 lubricants on Nano-miniature connectors. When they were 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 20,000,000 fretting cycles. MIL-L-87177 modified by addition of Teflon powder delayed first failure to beyond 5 million fretting cycles. Best results were obtained when Teflon was used and also when both the straight and modified lubricants were poured into and then out of the connector.

CLT: X-10 lubricant delayed the 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 that was terminated without failure. CLT: X-10 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.

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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 10 million cycles. When we used a MIL-L-87177 lubricant to which Teflon powder had been added, 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 developed by Dr. Aukland, known as CLT: X-10. This lubricant was able to prevent the ultimate failure of one connector for more than 55 million cycles and another for more than 10 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 certain 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 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 B2, 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 CLT: X-10 lubricant. In Test L it was brushed into the socket side. In Test M it 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.

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	X-10 recovered to 0 failures
A2	51	CLT: X-10	brush in socket	0	4	0.03 ohms		after 421,170 additional cycles
B	51	none	-	40,997	8	680 K ohms	12×10^6	
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
E1	26	none	brush in socket	45,238	9	490 K ohms	13×10^6	15×10^6 cycles
E2	25	MIL-L-87177	brush in socket	639	2	6 ohms		Test E1 pins (re)lubed and
E2	26	MIL-L-87177	brush in socket	25	12	200 K ohms		run 6×10^6 cycles
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 + Teflon	brush in socket	5.3×10^6	5	10 K ohms	7×10^6	stopped at 7.2×10^6 cycles
K	44	MIL + Teflon	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	CLT: X-10	brush in socket	$>55 \times 10^6$	5	>100K ohms	56×10^6	
M	44	CLT: X-10	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 CLT: X-10 lubricant. The connector pair was separated, lubricated with CLT: X-10 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, CLT: X-10 lubricant was able to restore all 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 CLT: X-10 lubricant was able to do after some 400 thousand additional fretting cycles in Test C.

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 round 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 round connector. In this case, a modification of the MIL-L-87177 lubricant was used that included addition of 1micron Teflon powder particles to the material. 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 did not include Teflon powder, 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 the Teflon modified MIL-L-87177 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 CLT: X-10 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 CLT: X-10 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 and 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 concluded that an application in which these connectors were subjected to vibration sufficient to cause fretting corrosion would be highly 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 is greatly improving the fretting susceptability 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 contacted George Kitchen at International Lubrication and Fuel Consultants to see if there might be some improvement available in the lubricant. In response, Dr. Kitchen provided us with lubricant modified by the addition of Teflon powder. 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 whatsoever 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. It is possible that the Teflon enhanced lubricant may provide better protection against fretting corrosion, but more work needs to be done to separate the Teflon effect from the application technique effect.

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 and K, run with straight and Teflon modified MIL-L-87177 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 even to both sides of the interconnection, that would yield still better results. More work needs to be done in this area.

CLT: X-10 Lubricant

In Tests A2, L and M of this series, the connectors were treated with CLT: X-10, a lubricant formulated by Connector Lubricant Technology of Las Cruces, NM.

In test A2, we demonstrated that CLT: X-10 lubrication 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, MIL-L-87177 was not able to recover similarily fretting damaged contacts in test C2.

In Test L, X-10 was able to provide protection against fretting corrosion for more than 55 million cycles. And in Test M, X-10 was able to provide protection for the 20 million cycles that the test was run before it was stopped. Judging from these test results on the criterion of preventing fretting corrosion alone, CLT: X-10 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 MIL-L-87177 lubricant in two different configurations, with Teflon powder and without. Another connector lubrication, CLT: X-10, 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 lubricvant delayed the onset of first failure to between 430 thousand and 20 million fretting cycles. Teflon modified MIL-L-87177 lubricant delayed the detection of the first failure to beyond 5 million fretting cycles. The contact resistance of connectors lubricated with 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 addition of the Teflon powder to the MIL-L-87177 lubricant and the application technique. The best results were obtained when the Teflon powder was used and also when both the Teflon 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.

CLT: X-10 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. CLT: X-10 lubrication 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.

APPENDIX A

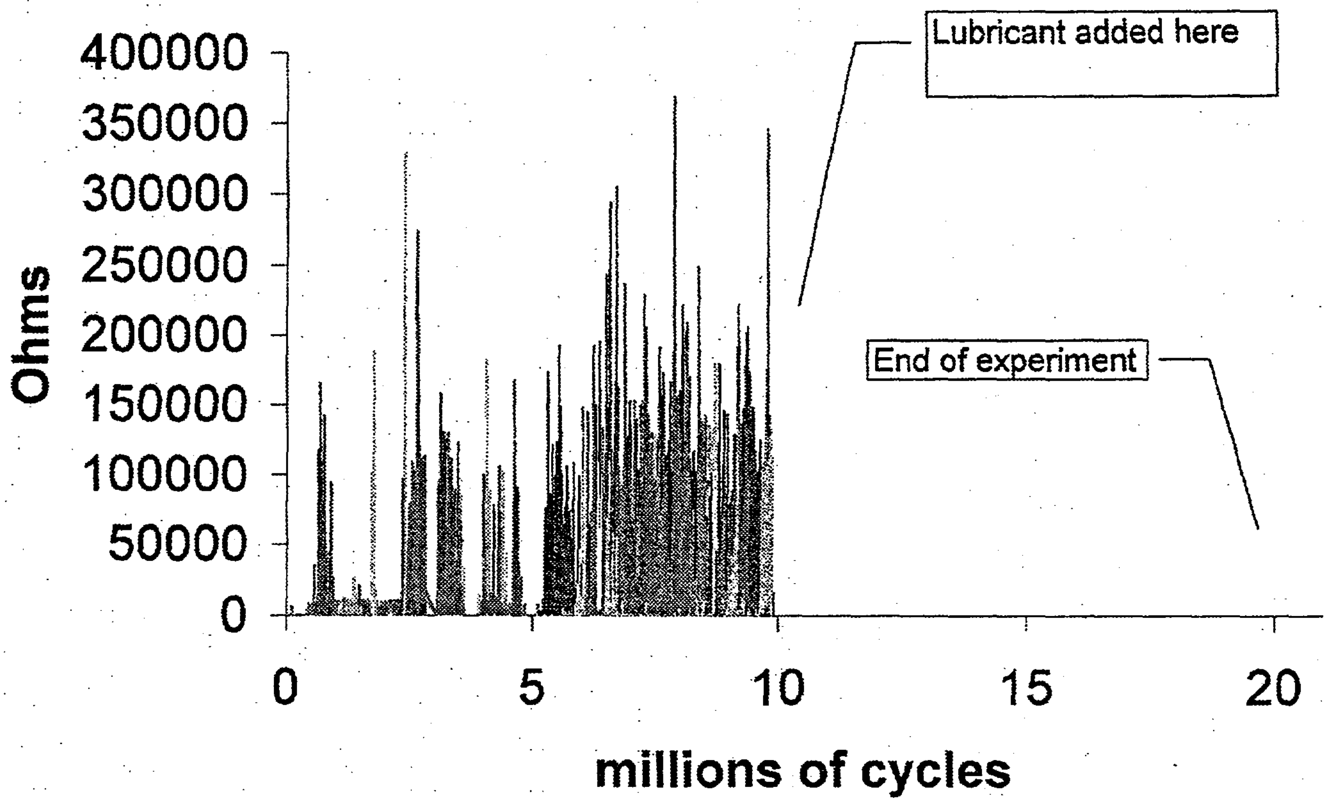

Figure A1. Maximum resistance of all failed pins (resistance > 0.5 ohm) throughout Test A. CLT: X-10 Lubricant was added at 10 million cycles.

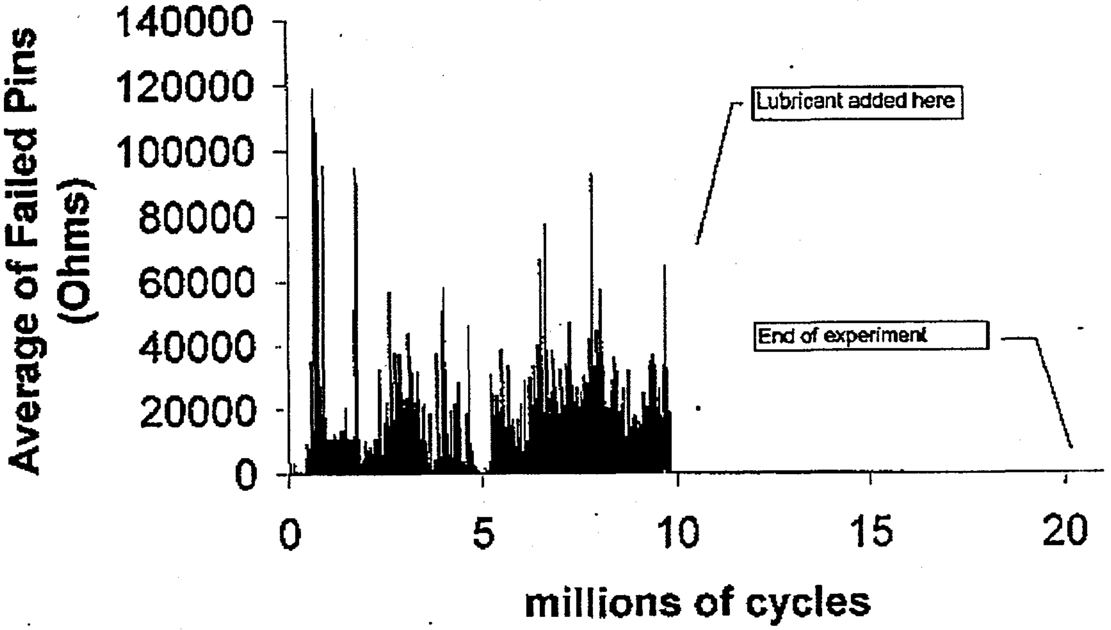

Figure A2. Average resistance of all failed pins (resistance > 0.5 ohm) throughout Test A. CLT: X-10 Lubricant was added at 10 million cycles.

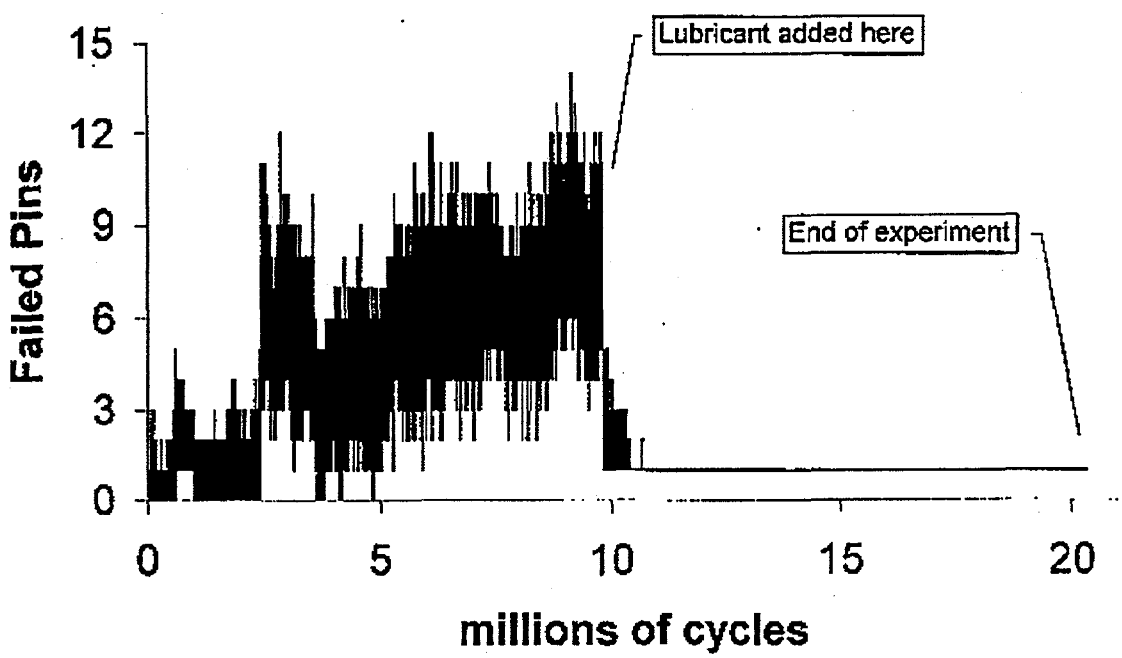

Figure A3. Number of pins in failure throughout Test A.