Connector Performance
on *New Vs Service-Aged Conductor, Part 2*

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***Abstract* - Our initial paper[1] on connector performance told of failures that Pacific Gas and Electric Company experienced with overhead line connections, especially as applied to service-aged conductor. It revealed PG&E's discontinued use of all-aluminum automatic line splices on AAC in exchange for ACSR automatic splices on both AAC and ACSR type conductors. The change was prompted not only by service outages, but by the failure of the all-aluminum splices to meet ANSI C119.4 current cycling performance criteria when installed on service-aged conductor.**

We also outlined a series of ANSI type tests for non-tension connectors applied to 397.5 kcmil AAC, 4 ACSR, and 6 AWG solid copper. Each of the three conductor sizes was to be tested in three independent circuits with the connectors installed on unused cleaned conductor, service-aged cleaned conductor, and service-aged uncleaned conductor.

This paper discusses connector performance on the 397.5 kcmil AAC when current cycled and power tested to the protocol of ANSI C119.4 and IEEE 837. And due to the quantity of failed test samples, it reiterates the need for strengthening ANSI C119.4 to include a test for a class of connectors which qualify for installation on corroded or aged conductor.

INTRODUCTION

Historically, PG&E has used bolted parallel-groove clamps as its primary means of making non-tension tap connections. This connector type has been used because we use hot sticks for working on energized conductors, and their installation with live-line tools is relatively simple.

Over the last several years, the Company has noticed an increase in the reported failure rate of these connectors. As a result, we began to infrared survey our overhead facilities and discovered hundreds of connectors running hot. The increased failures, infrared survey results, and other factors, prompted us to create our Connector Task Force. The task force is made up of representatives from our six operating regions, the Technical and Construction Services staff, the Technical and Ecological Services test facility, and the Safety, Health, and Claims Department.

Connector Task Force Charter:

The purpose of the study is to evaluate the current technology for making connections on copper and aluminum on our overhead primary and secondary distribution systems and recommend a system for PG&E that provides reliability and safety for the public and our employees.

All systems will be evaluated for compatibility with existing work practices, existing live-line tools, and anticipated rubber gloving work practices and procedures. To the extent practicable, any new system should take advantage of connectors and tools already on the PG&E system, and while economic considerations need to be identified, they will not direct the decision.

In reviewing the ANSI test requirements, we were concerned that the testing was only done on unused conductor. In our judgment, it did not represent actual field conditions. To have a better feel for what construction personnel would be expected to encounter in day-to-day operations, we decided testing should be done on aged conductor also.

Consequently, we elected to run three simultaneous test circuits (with connectors assembled in a series loop). One loop would be unused conductor, wire bushed cleaned at the connection location with corrosion inhibitor applied. This loop is the standard ANSI C119.4 (C119.4) loop. Another loop would be service-aged conductor that had been removed from the field, also wire brushed with inhibitor applied. And a third loop would be service-aged, uncleaned, with the connectors installed just as they came out of the package. Note, other than for test purposes, PG&E does not condone the installation of connectors on uncleaned conductor.

TESTING 397.5 AAC

We initially selected 10 non-tension connector types to be evaluated, but rejected one since it was a connection system the Company does not anticipate using. Of the nine types tested, four were compression: the dieless sleeve, the barrel sleeve, the compression "6", and the compression "H"; three were bolted: the 2-bolt parallel-groove (PG), the bolted wedge, and the 1-bolt vise; and two types were fired wedges. A set of four connectors of each type were installed in each loop for a total of 36 connectors per loop. We planned to electrically current cycle the loops 500 times with each current-ON period and each current-OFF period lasting 90 minutes.

Table 1 is a connector identification cross-reference showing the entire group of connectors discussed in this paper. Connectors listed under "paper terminology" represent both the shape and label abbreviation, to coordinate the name with visual recognition. For example, the compression "6" has this figure's profile prior to being installed. The fired wedge uses an explosive charge to seat a metallic shaped wedge to initiate the connection.

Results from the initial test show a large number of connector failures occurred on the aged conductor (hereafter referenced as aged #1 conductor). This prompted a second test on service-aged conductor (aged #2) where new connector sets were installed on both cleaned and uncleaned 397.5 kcmil AAC. The aged #2 conductor for the second test was obtained from a different distribution circuit than the first. The inner strands of this conductor had considerably less presence of corrosion byproducts (particulate). Most of the connector types from the first test were re-evaluated along with some new additions.

Four connectors from each of the following types were tested on service-aged #2 cleaned conductor: the 2-bolt vise, the eyelet vise, and the 3-bolt PG. On service-aged #2 uncleaned conductor we had four of the: compression "H"s, two manufacturers' fired wedges, the hydraulic wedge, and the three bolted connector types listed above for the aged #2 cleaned conductor. A total of 40 connectors were tested on the aged #2 conductors with both cleaned and uncleaned setups installed in one loop.

A test matrix of connector and conductor combinations was developed for presenting the results. The matrix (Fig. 1) shows the conductors for the first three test loops as unused

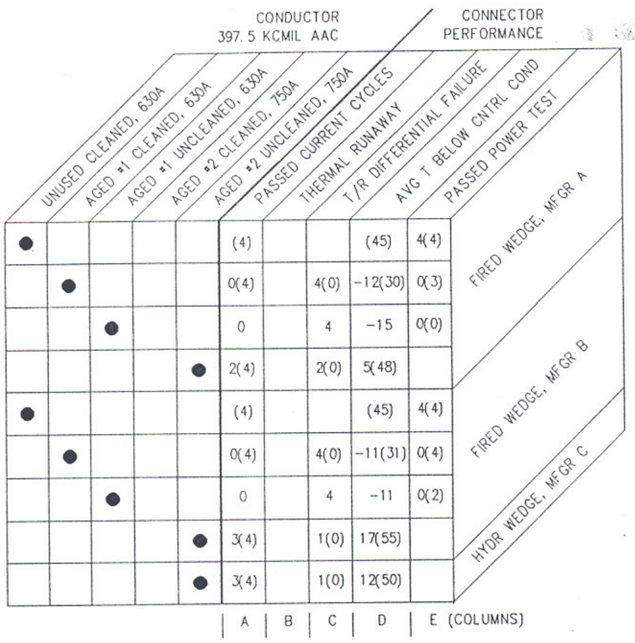
TABLE 1
CONNECTOR CROSS-REFERENCE

Paper Terminology	Industry Terminology
Fired wedge	Power assisted wedge connector
Hydraulic wedge	Hydraulically installed wedge connector
Compression "6"	YP-C compression connector
Compression "H"	H-type compression connector
Dieless sleeve	Dieless splicing sleeve compression connector
Barrel sleeve	Splicing sleeve compression connector
1-bolt vise	1-bolt vise connector
2-bolt vise	2-bolt vise connector
Eyelet vise	Hot line tap connector
2-bolt PG	2-bolt parallel groove clamp (PG)
3-bolt PG	3-bolt parallel groove clamp (PG)
Bolted wedge	Bolted wedge connector

cleaned, aged #1 (heavy corrosion) cleaned, and aged #1 uncleaned. For the second test, the conductors are designated aged #2 (light corrosion) cleaned and aged #2 uncleaned. Each loop's test current in amperes for which the test results are based is shown following the conductor designation.

Most of the matrix cells in the connector performance columns contain one or two numbers. These numbers relate to a quantity of connectors or connector temperature depending on the column designation and foot notes. If a cell contains only one number, then the condition that would justify a second number is not applicable. Similar logic applies to blank cells. In columns A through D for example, when testing on unused conductor, an aged control conductor was not installed in the loop, so only one number appears in these cells. Likewise, when testing on aged #1 uncleaned conductor an unused control conductor was not installed in the loop. However, with the experience gained from these loops, unused *and* aged control conductors were installed in the remaining loops. C119.4 specifies the temperature of the connector shall not exceed the temperature of the control conductor. *Column D shows that while a connector temperature is above the temperature of the aged control conductor, it may remain below the temperature of the unused control conductor. And depending on which control conductor is used as the reference often determined whether or not the connector passed.*

In accordance with C119.4, we found that 630 amps was required to raise the temperature of unused 397.5 AAC conductor 100 °C above ambient temperature. It required 750 amps to raise the aged conductor temperature 100 degrees. *The rough and dark surface of the aged conductors enhances the heat transfer characteristics (emissivity) causing the aged conductor to require more current to produce the same temperature rise.*



CURRENT CYCLE TEST (SIMILAR TO ANSI C119.4)

- T/R = TEMPERATURE AND/OR RESISTANCE
- COLUMNS A, B, & C: CONNECTOR QUANTITY
- COLUMN D: TEMPERATURE, DEGREES C OF CONNECTOR SET WITHOUT A THERMAL RUNAWAY
- RESULTS OUTSIDE PARENTHESIS *(-) ARE BASED ON AGED CNTRL. COND.
- RESULTS INSIDE PARENTHESIS -(*) ARE BASED ON UNUSED CNTRL. COND.

POWER TEST (SIMILAR TO IEEE 837)

- COLUMN E: CONNECTOR QUANTITY
- RESULTS OUTSIDE PARENTHESIS *(-) ARE BASED ON THE PRETEST RESISTANCE, POST TEST RESISTANCE, AND VISIBLE MOVEMENT OF THE CONDUCTOR WITH RESPECT TO THE CONNECTOR.
- RESULTS INSIDE PARENTHESIS -(*) ARE BASED ON THE POST TEST RESISTANCE AND VISIBLE MOVEMENT OF THE COND. WITH RESPECT TO THE CONNECTOR.

NOTES FROM THE PRECEDING APPLY TO ALL MATRICES.

Fig. 1. Power wedge connectors test and results matrix

The notes below Fig. 1 apply to connector performance. Columns A through D relate to the current cycle test criteria of C119.4. Column E relates to the power test or electromagnetic force withstand (EMFW) test described in IEEE Standard 837. Both of these documents served as testing guides, however some variance was necessary due to discrepancies between the two standards. For example, the connector/conductor sample lengths specified by the two standards are different. Since the C119.4 test was the primary test, and first run, all physical dimensions conform to it. We also reduced the current specified in IEEE 837 to 30,000 amps which is more in line with the fault current capabilities near the bus at some of our larger substations. The number of current surges per connector (three) and the duration (12 cycles) is the same as specified in IEEE 837.

Column E shows the IEEE 837 test results that both include and omit the pretest (initial) resistance criteria which were difficult to achieve with connectors installed on the aged #1 conductor. Reason, the resistance of the connection to the conductor is proportional to the number of conductor strands which are cleaned either prior to or during the application of the connector. *Laboratory tests have confirmed that the 7 uncleaned inner strands of the 19 strand aged #1 conductor are essentially not a part of the electrical circuit. Even under compressive loading, the strand-to-strand resistance of most inner strands was tens of kilohms! This was not the case for the aged #2 conductor.*

EPRI has contracted a study to investigate methods for cleaning the inner strands of corroded conductor. We have provided the contractor with conductor, and the results of our tests.

Results

The following connector sets on unused cleaned conductor met the C119.4 resistance and temperature criteria: all of the fired wedges, all of the compression types and the 1-bolt vises, two of the 2-bolt PGs, and one of the bolted wedges (Figs. 1 through 3). In the EMFW (power) test, on unused conductor, all of the fired wedges, compression "H"s, and the dieless sleeves met all of the IEEE 837 criteria. The remaining compression types had three out of four connectors pass. If the IEEE 837 pretest resistance criteria were omitted, all of the bolted types except for one bolted wedge would have passed on the unused 397.5 kcmil AAC.

On the aged #1 cleaned and uncleaned conductors, every connector exceeded the temperature of the aged control conductor within the first C119.4 test cycle, and many were headed toward thermal runaway. The test procedure was then modified to enable an evaluation.

Under the modified test plan, beginning with the aged #1 uncleaned conductor, current cycling began at 50 amps, then current was raised and cycled, similar to a ratchet. Fig. 4 shows temperature rise versus current for the various connector types. Only the fired wedges and the barrel sleeves completed 106 cycles at various current increments from 50 to 750 amps without thermal runaway.

The aged #1 cleaned conductor modified test, with both unused and aged control conductors installed, also included cycling increments of current from 50 to 750 amps. Current then was set to 630 amps and cycled for 129 intervals. Connectors tested on the aged #1 cleaned which did not

Unused cleaned, 630A	Aged #1 cleaned, 630A	Aged #1 uncleaned, 630A	Aged #2 cleaned, 750A	Aged #2 uncleaned, 750A	Passed current cycles	Thermal runaway	T/R differential failure	Avg T below cntrl cond	Passed power test	Connector
●					(4)			(23)	3(4)	COMPR "6"
	●				0(2)	2(2)	2(0)		0(4)	
		●				4			0(3)	
●					(4)			(33)	4(4)	COMPR "H", MFGR D
	●				0(4)		4(0)	-13(29)	0(4)	
		●				4			0(3)	
			●			4(4)				COMPR "H", MFGR E
●					(4)			(23)	4(4)	DIELESS SLEEVE
	●				0(2)	1(1)	3(1)		0(4)	
		●				4			0(3)	
●					(4)			(32)	3(4)	BARREL SLEEVE
	●				0(3)	1(1)	3(0)		0(4)	
		●					4	-10	0(4)	

CONDUCTOR 397.5 KCMIL AAC / CONNECTOR PERFORMANCE

Fig. 2. Compression connectors test and results matrix

avalanche to thermal runaway were: all of the fired wedges, compression "H"s and 1-bolt vises, three of the barrel and dieless sleeves, and two of the compression "6"s and bolted wedges, and one of the 2-bolt PGs. Of these connectors, several had temperatures that even exceeded the temperature of the unused control conductor, they were: one of the four 1-bolt vises, one of the two remaining bolted wedges, one of the three dieless sleeves, and the remaining 2-bolt PG.

None of the connectors installed on either of the aged #1 conductors met all of the EMFW test criteria. The compression types gave the overall best performance. It was not uncommon for the compression connector/conductor joints to show a decrease in resistance as a result of the current surges. The fired wedges performed slightly better than the bolted types on the aged #1 uncleaned conductor, and tested about equal to the compression types on the aged #1 cleaned conductor.

All of the connectors tested on the aged #2 conductor were subjected to at least 500 current cycles. Fig. 3 shows the 2-bolt vise and the eyelet vise passed the C119.4 criteria on the aged #2 cleaned conductor with a comfortable margin, even when referenced to the aged control conductor. The third and last connector set tested on the aged #2 cleaned cable was the 3-bolt PG (Fig. 3). All four samples passed when referenced to the unused control conductor, and two passed when referenced to the aged control conductor.

On the aged #2 uncleaned conductor, Fig. 1 shows all the fired and hydraulic wedges passed the C119.4 current cycle test when referenced to the unused control conductor, and eight of the 12 connectors passed when referenced to the aged control conductor. All of the compression "H"s, 2-bolt vises, and the eyelet vises experienced thermal runaway along with three of the four 3-bolt PGs.

Discussion

The preceding results show the fired and hydraulic wedges rank best of all the connectors tested, with the compression types ranking second and the bolted types third. The discussion to follow will reflect some of reasons for this ranking based on our experiences over the past three years of testing.

Unused cleaned, 630A	Aged #1 cleaned, 630A	Aged #1 uncleaned, 630A	Aged #2 cleaned, 750A	Aged #2 uncleaned, 750A	Passed current cycles	Thermal runaway	T/R differential failure	Avg T below cntrl cond	Passed power test	Connector
●					(4)			(31)	0(4)	1-BOLT VISE
	●				0(3)		4(1)	-25(18)	0(0)	
		●				4			0(0)	
			●		4(4)			34(68)		2-BOLT VISE
				●		4(4)				
			●		4(4)			19(53)		EYELET VISE
				●		4(4)				
●					(2)		(2)	(20)	0(4)	2-BOLT PG, MFGR F
	●					3(3)	1(1)		0(1)	
		●				4			0(0)	
			●		2(4)		2(0)	6(44)		3-BOLT PG, MFGR G
				●		3(3)	1(1)			
●					(1)	(2)	(1)		0(3)	BOLTED WEDGE
	●				0(1)	2(2)	2(1)		0(0)	
		●				4			0(0)	

CONDUCTOR 397.5 KCMIL AAC / CONNECTOR PERFORMANCE

Fig. 3. Bolted connectors test and results matrix

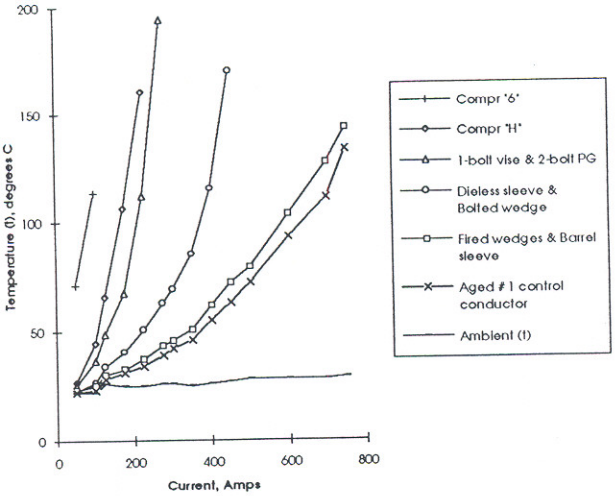


Fig. 4. Non-tension connectors on service aged #1 uncleaned 397.5 AAC

The fired and hydraulic wedges are the only connectors tested on all of the 397.5 kcmil AAC which have not had a single thermal runaway. These wedges are the only connectors tested which scrape the conductor outer surface during installation, thereby initiating some cleaning action. The compression type barrel sleeve for uni-size conductor apparently initiates some cleaning during installation as noted by the twisting action needed to apply the sleeve to the aged conductor. This probably accounts for the barrel sleeve being the only connector other than the fired wedge not to have consistently experienced thermal runaways on aged #1 uncleaned conductor.

The fired and hydraulic wedge's superior performance over the bolted wedge may be attributed to the C-member (shell) of the connector. It's our understanding that the fired and hydraulic wedge C's are either a rolled plate or an extrusion, depending on the manufacturer. The bolted wedge we tested has an aluminum alloy casting shape which may limit the connector's ability to flex[2], and compensate for the conductor thermal expansion.

The bolted connectors were the easiest to apply, in the wrong manner. We concur with Jackson[3] that choosing the correct bolt and washer, and applying the correct contact pressure to properly prepared surfaces is critical to the success of the connection. Bolts were initially torqued to manufacturer's specifications, then torque was measured after the current cycle test. Post test torques ranged from hand tight to 100 percent of the installed values. The post test torque is the torque after break-a-away in the tightening or clockwise direction. Connectors with the higher post test bolting torques generally performed better electrically.

To obtain a better understanding of bolt torque losses, a mechanical stress analysis[4] was performed on two 2-bolt PGs (with aluminum bolts) installed on the aged #2 conductor, and current cycled at 750 amps. Bondable type strain gages were mounted on each connector half to measure the stresses. An ultrasonic device was used to measure bolt elongation. Over the 330 hours of monitoring, the greatest decrease in compressive stresses on the connector and bolt elongation occurred in the first 72 hours. The decrease in bolt elongation indicated the bolts were not yielding. The decrease in compressive bending stress on the PG shell halves indicated the connector was relaxing to its pretest condition (an increase in compressive stress would indicate the connector was yielding). Since neither component was yielding, *the analysis concluded the conductor was deforming, experiencing stress relaxation.*

Fig. 5 shows the performance of a 3-bolt PG on aged #2 cleaned conductor. Notice how the temperature differential between the connector and the aged control conductor is diminishing with time. At cycle 660, while the connector was still marginally passing test criteria, the bolt torque was measured (11 ft-lbf. 3-bolt avg) and re-tightened to the installed torque of 25 ft-lbf. During the next current-ON period, connector temperature took an immediate step change increase and initiated a temperature differential failure. Resistance, when next measured, had increased from 234 to 256 microhms causing a resistance stability failure. Jackson[3] concludes that the re-tightening establishes new contact points within the joint that had become oxidized over time, and recommends the connection be completely dismantled and contact surface re-abraded. Note, PG&E's crew policy is to remove a defective connector, wire brush the conductor, apply corrosion inhibitor with a separate wire brush, and install a new connector.

Temperature in Fig. 5 is measured once every three hours at the end of each current-ON cycle. The small oscillations in the ambient temperature reflect the 24 hour variations. These small changes are magnified in the temperature of the connector and control conductors. The temperature difference between the aged control conductor and connector is smallest when the ambient temperature is at the daily peak. If the connector was about to fail on differential temperature, then the failure may be avoided if the 11 measurements required by C119.4 were recorded when ambient was lowest. The standard allows for ambient to range from 15 to 35 °C. It is therefore reasonable to conclude that a marginal connector could pass or fail depending on the ambient of the test cell.

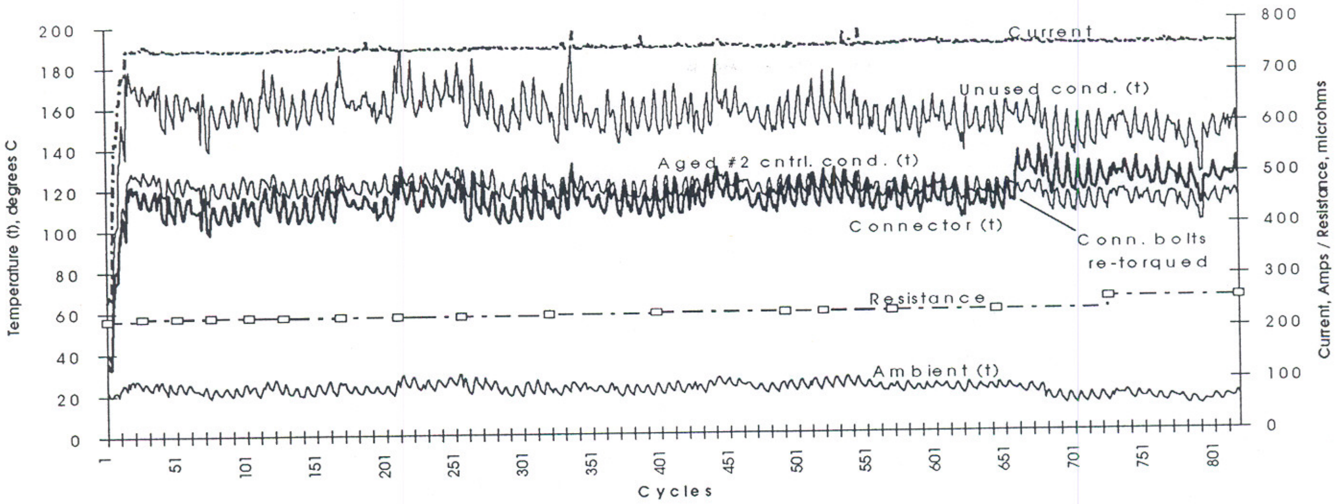


Fig. 5. 3-bolt PG performance on service-aged #2 cleaned 397.5 kcmil AAC

Testing on unused conductor to the present standard does not replicate testing on aged conductor, as the quantity of failures has shown. The problem is, how to define an aged conductor for a test standard. We tried to artificially age unused conductor with an acidified synthetic sea water (fog) test in accordance with ASTM G85 Annex A3. The surface of the conductor outer strands developed a heavy coating of soft aluminum oxide, but the inner strands were only slightly effected, which was unacceptable for our tests.

If the standard current cycle test must be performed on unused conductor, then there may be a way of predicting failure even though the connector passes present testing criteria. Fig. 6 shows line graph results of two connectors of the same type installed on unused conductor. The plots for Conn. #1, associated with the label Cx1, failed the C119.4 temperature stability requirement based on 11 measurements recorded at specified intervals within the first 500 current cycles. The connector actually failed when the temperature of Cx1 became less than the continuous average of Cx1 minus 10 degrees at cycle 426. Conn. #2, associated with the label Cx2, passed the 500 cycle test even though the two data lines are obviously converging. By using the *least squares* method to plot a linear regression line of the Cx2 data, we predict Conn. #2 will have a temperature stability failure near cycle 1200 if the temperature difference between the control conductor and the connector continues to decline on its present course.

ANSI C119 Subcommittee

Several manufacturers and utilities such as PG&E are members of the Subcommittee on Overhead Connectors Accredited Standards Committee C119. The subcommittee has working groups on performance, on testing, and on extra heavy duty connectors. The Working Group on Extra Heavy Duty Connectors has the primary responsibility of addressing the issue of connecting to service aged conductor.

Group members with testing facilities are conducting simultaneous performance evaluations of connectors on unused conductor at elevated temperatures, with tighter stability limits, to determine if tests on aged conductor can be replicated. These trials have shown that a few connectors previously qualifying under C119.4 would also meet the stricter criteria. Perhaps these efforts will enhance product design; they have already gained the support of the utility customer. We applaud the members' work and the support of their companies.

Conclusions

Current cycle testing and EMFW testing the three major non-tension connector groups on service aged conductors show the need for: 1.) a procedure for cleaning conductor inner strands, 2.) improved testing standards, and 3.) extra heavy duty connector products. Of the three connector groups, the fired and hydraulic wedges provided the most consistent overall test results.

The C119.4 test criteria need to be strengthened. The existing standard does not adequately address the issue of placing connectors on aged conductor. We believe failures in the field are the result of the conductor and connector aging process coupled with increased loading as we attempt to operate lines closer to their thermal design limits.

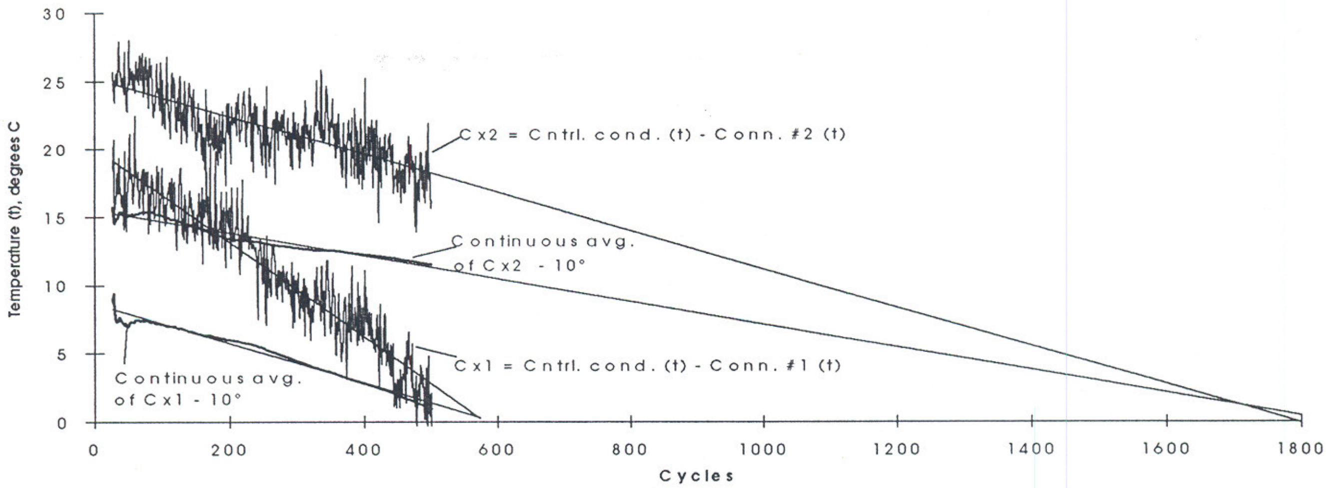


Fig. 6. Temperature stability failure prediction of two connectors installed on unused cleaned 397.5 kcmil AAC

The test criteria should be modified to provide for higher temperature rise, an increase in the number of test cycles or both. Another approach might be to adopt a performance based type of test where a current in excess of maximum normal is used as the base. Again, our fundamental belief is the test should duplicate field situations as closely as practicable.

Acknowledgment

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Biographies

James D. Sprecher (M' 79) received a Bachelor of Science Degree in Electrical Engineering from the University of Wyoming in 1967 and a Master of Science Degree in Engineering Management from Santa Clara University in 1990. Mr. Sprecher has worked for Pacific Gas and Electric Company for 26 years in various system engineering and operating positions and has held department manager positions during the past 23 years, most recently as the Gas and Electric Operations Manager in San Francisco Division. He is currently a Principal Electric Engineer in the Distribution Department and Program Manager of PG&E's Connector Task Force.

M. Larry Rockfield (A' 73) since 1964 has worked for Pacific Gas and Electric Company at the Department of Engineering Research, later to become the Technical and Ecological Services Department. As a supervisor, he was responsible for electrical testing and analysis of the current cycle and power tests on non-tension connectors. In 1993 he retired from PG&E and joined Power Quality and Electrical Systems, Inc. as a consultant.

Tony Nothelfer (S' 74, M' 78) received a B.S.E. from San Francisco State University in 1976, and a M.S.E.E. from the University of Southern California in 1978.

He has been with PG&E's Technical and Ecological Services since 1984 performing tests and analyses of diverse electric utility problems. His interests include high voltage and transient measurement instrumentation.

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