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Performance of Branch Circuit Electrical Terminations of Copper and Aluminum Non-Metallic Sheathed Cable

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Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

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Final Report

Prepared for

Naval Facilities Engineering Command
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Directorate of Civil Engineering
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Larry W. Masters, Elizabeth J. Clark and Edward J. Embree

ABSTRACT

A study was performed to provide the Tri-Services Committee on Building Materials with guidelines regarding the use of aluminum branch circuit wiring in military buildings. The first part of the study consisted of identifying military bases which contained buildings with aluminum wired branch circuits. Personnel at a number of the bases were contacted in order to estimate the extent of observed problems. Laboratory tests were performed on CO/ALR and non-CO/ALR duplex receptacles wired with both aluminum and copper non-metallic sheathed cable. Overheating of aluminum wired termination points was observed with some receptacles in a current cycling test using non-CO/ALR receptacles at screw torque levels of 0.023 and 0.069 kg-m (2 and 6 lb-in). Aluminum wired non-CO/ALR receptacles tested at 0.138 kg-m (12 lb-in) screw torque showed no signs of overheating and copper wired non-CO/ALR receptacles showed no signs of overheating regardless of screw torque.

This report presents the findings of the study and includes guidelines regarding the use of aluminum branch circuit wiring in military buildings.

Key Words: Aluminum wiring; branch circuits; copper wiring; military buildings.

1. INTRODUCTION

1.1 Background

Both copper and aluminum wire have been used for conducting current in electrical branch circuits. Prior to the mid 1960's, copper wire was used almost exclusively in branch circuits but, in the mid to late 1960's, the use of aluminum wire in branch circuits increased substantially. About that same time, the use of plated steel for wire binding screws of receptacles and switches became prevalent. The substitution of aluminum for copper wire and of steel for brass wire binding screws was largely due to the increased cost and limited availability of copper during the late 1960's.

By 1969, Underwriter's Laboratories Inc. (UL) had begun to receive reports of problems in the field associated with aluminum electrical wiring [1]*. The reported problems were primarily overheating at points in branch circuits where the wiring was joined to receptacles and switches (termination points). As a result of these field reports, UL re-evaluated and revised its test specifications and subsequently recommended that only those wiring devices (receptacles and switches) with a "CO/ALR" label be used with aluminum wiring. (The CO/ALR label means that the wiring devices have complied with the revised UL test specifications.) CO/ALR rated wiring devices can be used with copper as well as aluminum wire. Devices which complied with the revised UL test specification all contained brass wire binding screws and wire restraints. Some of the CO/ALR rated devices also contained indium plated contact components.

In addition to the changes in wiring devices as a result of field problems, changes were also made in the alloys used for aluminum wiring. The aluminum wiring used prior to about 1972 has been shown by Battelle Columbus Laboratories [2] to exhibit high stress relaxation and to be physically difficult to work with. The post-1972 wiring was formulated to overcome some of the problems observed with pre-1972 wiring.

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*Numbers in brackets refer to references at the end of this paper.

In 1974, the Consumer Product Safety Commission (CPSC) requested that a study be performed by the National Bureau of Standards (NBS) to determine if terminations of aluminum electrical wiring produced a potential hazard in residential branch circuits. Reports prepared for the CPSC presented the NBS findings in 1974 [1, 3]. Subsequent reports discussed conditions under which loose terminations (0 kg-m screw torque) of both copper and aluminum could overheat [4] and presented the results of cyclic tests of crimp connectors [5].

In 1975, the Tri-Services Committee on Building Materials requested the Center for Building Technology of NBS to perform additional studies in order to provide guidelines on the use of aluminum wiring in military buildings. The purpose of this report is to present the findings of the latter study.

1.2 Scope of Study

This study had four objectives: 1) to estimate the extent of use of aluminum branch circuit wiring in military buildings, 2) to identify military installations in which problems had occurred, 3) to perform laboratory studies of electrical terminations and 4) to provide guidelines on the use of aluminum wiring in military buildings.

Prior laboratory studies [3, 4] had shown that totally loose termination points (0 kg-m screw torque) could result in overheating with both copper and aluminum wire. Totally loose terminations were not tested further in this study. This study consisted of identifying and contacting military bases where aluminum branch circuit wiring has been used and performing laboratory studies with both CO/ALR and non-CO/ALR duplex receptacles.

The laboratory studies were performed using aluminum wiring of the post-1972 type. It would have been desirable to perform tests with pre-1972 wiring to provide guidelines on actions to take regarding that type of wire. However, when the laboratory studies were started, the pre-1972 alloys were not available.

2. DISTRIBUTION OF ALUMINUM WIRED BRANCH CIRCUITS IN MILITARY BUILDINGS

A Department of Defense (DoD) survey, performed in 1974, was used as the initial source of information to estimate the extent of use of aluminum branch circuit wiring in military buildings and to identify installations in which problems had been observed. Personnel at a number of the bases where aluminum branch circuit wiring had been used were then contacted by telephone to obtain additional information. Table 1 summarizes the information obtained from the DoD survey and the telephone contacts for Air Force, Army and Navy residential units. The table includes data for aluminum and copper-clad aluminum wire of sizes #6 AWG and smaller.

In addition to the use of aluminum wire in residential units, a number of bases have a limited number of other types of buildings with aluminum wired branch circuits. These include Cannon AFB, New Mexico; McChord AFB, Washington; Norton AFB, California; Rickenbacker AFB, Ohio; Fort Polk, Louisiana (Army); Fort Rucker, Alabama (Army); and the U.S. Army Aeronautical Depot Maintenance Center, Corpus Christi, Texas.

Based on the data in table 1, it is estimated that about 4100 military dwelling units contain aluminum wired branch circuits. Approximately 2350 of these units are located on Air Force bases, 1300 on Navy bases and 450 on Army bases. Overheated termination points, as determined by observations such as unusually warm receptacle or switch covers, degraded wiring devices or degraded poly(vinyl chloride) wire insulation, have been observed by base personnel in a number of installations as summarized in table 1. Overheated terminals have generally been attributed by base personnel to loose connections and poor workmanship.

3. LABORATORY TESTS AND RESULTS

3.1 Current Cycling Tests with Non-CO/ALR Receptacles

3.1.1 Scope

Two types of typical non-CO/ALR duplex receptacles were installed in a laboratory wall structure. One type of receptacle contained zinc plated steel wire binding screws and the other type contained brass wire binding screws. The devices were wired with either copper or aluminum non-metallic sheathed cable at three levels of screw torque. Current (15 amperes) was cycled through the circuit and the breakoff tab temperatures were monitored.

The purpose of the test was to evaluate the performance of termination points under conditions that simulate field conditions. The test was not designed to be an accelerated test. Rather, it was intended to complement accelerated tests which had been performed in other laboratories [2, 6]. The test was started in July 1974 and continued for 27 months.

3.1.2 Procedure

Thirty-six non-CO/ALR grounding type duplex receptacles, which were rated for 15 ampere loads, were installed in a laboratory wall structure. The wall structure, which was about 2.4 x 4.5 m (8 x 15 ft) in size, was constructed of 2 x 4's and plywood paneling and included 8.8 cm (3.5 in) of foil faced fiberglass insulation. Half of the receptacles contained zinc plated steel wire binding screws while the remainder contained brass screws. The wall had four rows (A, B, C and D) of nine receptacles, aligned in columns. Figure 1 illustrates the arrangement of the receptacles in the wall structure and figure 2 is a diagram of the circuit. Rows A and C contained receptacles with steel wire binding screws while Rows B and D contained receptacles with brass wire binding screws. Rows A and B were wired with #10 AWG aluminum non-metallic sheathed cable and Rows C and D with #12 AWG copper non-metallic sheathed cable. Both types of cable contained two conductors with a grounding conductor and the aluminum wire used in the test was representative of that commercially available in mid-1974. Three-quarter, planar wire loops were used in all terminations (e.g. the wire under the screw head formed a 3/4 loop and the plane of the loop was parallel to the plane of the screw head). The screws of two receptacles (Columns 1 and 2) in each row were tightened to 0.023 kg-m (2 lb-in) torque. The screws of three receptacles (Columns 3, 4 and 5) in each row were torqued to 0.069 kg-m (6 lb-in) and the remaining four receptacles (Columns 6, 7, 8 and 9) in each row were torqued to 0.138 kg-m (12 lb-in) as illustrated in figure 1. In each case, the receptacles were installed in standard metal boxes having a volume of about 200 cm^3 (12 in^3). The screw torque was applied after installing the receptacles in the boxes to ensure that the actual screw torque was known. (If screws had been torqued prior to installing receptacles in the boxes, they may have been either tightened or loosened during the process of pushing the receptacle into the box.) Copper constantan thermocouples (28 gauge) were installed on the black wire (non-grounded) side breakoff tab of each receptacle and in the open space behind the receptacle in each box. An additional thermocouple was used to monitor the ambient air temperature in the wall structure. The voltage drop across the two black wire termination points on each receptacle was measured prior to initiating the test. The procedure used was to apply a 10 ampere load, place probes on each of the black wires near the termination point (note points A and B in figure 3) and read the voltage drop on a voltmeter. From the voltage drop reading, the resistance across the two termination points was calculated. The voltage drop was then remeasured at the end of twenty cycles and prior to removing receptacles from the wall.

The receptacles were wired to a load drawn by laboratory hot plates. The current load (15 amperes) from the 120 volt, 60 cycle main supply was applied to the receptacles in cycles of 3 1/2 hours ON and 1/2 hour OFF. Two ON/OFF cycles were completed each working day. The cycling was not continued overnight or on weekends. Initially, temperature readings were taken daily near the end of the ON period. After the completion of 20 cycles, temperatures were recorded in increments of ten cycles.

At the end of twenty cycles, twelve of the receptacles (one for each wire/screw/torque combination) were removed from the wall structure and prepared for metallographic examination. No other predesignated time interval was assigned for removal of receptacles. Rather, some receptacles were removed at various stages of overheating while others were removed at similar time intervals for comparison. When receptacles were removed the wire was cut 10-12 cm (4-5 inches) from the termination points and care was taken to avoid disturbing the terminals. Replicate receptacles were installed to replace those that had been removed.

3.1.3 Results and Discussion

The results for the four rows of receptacles are summarized in tables 2, 3, 4 and 5. The "Column Number" listed in the tables is the same as that in figure 1. The receptacles installed in each "Column Number" for each row are assigned a number (i.e., "Receptacle Number" 1 is the first receptacle installed; Receptacle Number 2 is its replacement, etc.). The tables also include screw torque, number of cycles completed, and black wire (non-grounded) breakoff tab temperature data. Several receptacles were also equipped with thermocouples on the white wire (grounded) breakoff tab during the experiment. These are noted in the table footnotes. The third cycle temperature is included as a measure of the initial operating temperature because it was observed that two initial cycles were required to obtain a stable operating temperature for many of the receptacles.

The tables also include the maximum recorded breakoff tab temperature and the cycle on which the maximum temperature occurred. Typically, the temperatures varied from day to day and from cycle to cycle. Figure 4 is a plot of the black wire breakoff tab temperature against the number of cycles for the aluminum wired brass screw receptacle (Row B, Column 1, Receptacle 1) that exhibited the maximum temperature in the wall experiment. It illustrates the types of fluctuations observed in temperature from cycle to cycle.

For the purpose of this report, "overheating" is defined as an increase of 10°C (18°F) or more above the average third cycle temperature for each row of receptacles.

Table 2 contains the test results for the Row A receptacles (steel screws/aluminum wire). The average third cycle breakoff tab temperature for the Row A receptacles was 55°C (131°F). Of the four receptacles installed at 0.023 kg-m (2 lb-in) screw torque, one (Column 2, Receptacle 2) exhibited overheating according to the above definition. The overheated receptacle exhibited a maximum black wire breakoff tab temperature of 110°C (230°F) on the 210th cycle. During the experiment, infrared thermography using an infrared (IR) television system was used to identify the termination points which were overheating. It was determined by infrared thermography that a terminal on the white wire side of this receptacle was overheating. At the end of 319 cycles a thermocouple was installed on the white wire breakoff tab. The white wire breakoff tab temperature was 88°C (191°F) on the 320th cycle and it remained relatively constant through the 390th cycle. The black wire breakoff tab temperature, which was 76°C (169°F) on the 320th cycle, remained relatively constant through the 390th cycle. The elevated temperature on the black wire side could have been due to either an overheated terminal or to heat transferred from the white wire side.

One additional Row A receptacle exhibited slight overheating. This receptacle (Column 4, Receptacle 2) was one of five installed at 0.069 kg-m (6 lb-in) screw torque. The maximum black wire breakoff tab temperature recorded was 66°C (150°F) on the 210th cycle. Infrared thermography studies showed that one white wire terminal on this receptacle was slightly overheating. At the end of 309 cycles, a thermocouple was installed on the white wire breakoff tab. The temperature measured by this thermocouple was 67°C (135°F) on the 310th cycle and it remained relatively constant through the 390th cycle. From the 310th through the 390th cycle the black wire breakoff tab temperature was slightly below the average third cycle temperature of the Row A receptacles. As shown in table 2, none of the five Row A receptacles tested at 0.138 kg-m (12 lb-in) screw torque showed signs of overheating.

Test data for the Row B receptacles (brass screws/aluminum wire) are summarized in table 3. The average third cycle breakoff tab temperature for the Row B receptacles was 59°C (138°F). Four of the six receptacles tested at 0.023 kg-m (2 lb-in) screw torque overheated. All four of the overheated receptacles were in Column 1 of the wall. The first receptacle installed in Column 1 had a black wire breakoff tab temperature of 199°C (389°F) after 68 cycles. At this point, the temperature decreased gradually to 57°C (135°F) after 120 cycles and remained relatively constant until the receptacle was removed from the wall at the end of 280 cycles. The decrease in temperature after 68 cycles was attributed to a wire to wire contact made about 2 inches from the termination points. The new contact was possible because of extensive degradation of the poly(vinyl chloride) (PVC) wire insulation. Figure 5 is a picture of this receptacle prior to its removal from the wall. The PVC degradation can be observed in the figure.

The initial resistances of the Row B receptacles in Column 1, as measured across the two black wire terminations (from points A to B in figure 3), were 8.3, 7.6, 2.7 and 3.8 milliohms for receptacles 1, 2, 3 and 4, respectively. These resistances include the resistance of the breakoff tab which was located between the two termination points. The breakoff tab resistance of a replicate receptacle was measured and found to be about 0.33 milliohms. Measurements of breakoff tab resistance are discussed in Section 3.4 of this report. The inital resistance values for the two receptacles in Column 2 were 2.0 and 1.2 milliohms, respectively. The initial values for all other Row B receptacles were less than 0.9 milliohms. Thus, all Row B receptacles with initial resistances of 2.7 milliohms or greater exhibited overheating while those with initial resistances of 2.0 or less did not overheat. The Column 2 receptacle with an initial resistance of 2.0 milliohms was cycled for only 20 cycles. This cycling time may not have been great enough to produce overheating. Based on these data, it appears that by measuring the initial resistance of brass screw receptacles wired with aluminum, there is a possibility of predicting whether or not the terminals will overheat in a relatively short period of time (2 years). The point above which overheating occurs is apparently between 1.2 and 2.7 milliohms, including the breakoff tab resistance. Additional studies are needed to determine if such measurements could be used as a tool in the field to identify potential future problems.

Row B, Column 1 receptacles 2 and 3 were also removed after overheating became obvious but before extensive degradation took place in order to study the termination point interfaces at various stages of degradation. The screw head/wire/contact plate interfaces of the overheated termination point of Receptacle 1 of Column 1 are shown in figure 6. The figure shows arcing pits and corrosion products resulting from the corrosion products on the same wire shown in figure 5. Figure 7 is a closeup of the wire surface which shows the corrosion products. Analysis of the surfaces in figure 6 by scanning electron microscopy and X-ray emission showed that the surfaces of all the interface materials contained aluminum, copper, zinc and large amounts of chloride [7]. The source of the chloride was almost certainly the degraded PVC wire insulation. No signs of overheating were observed on the Row B receptacles with screw torques of 0.069 kg-m (6 lb-in) or 0.138 kg-m (12 lb-in).

Tables 4 and 5 summarize the data for steel and brass screw receptacles, respectively, wired with #12 AWG copper wire. The average third cycle temperature of the Row C receptacles (table 4) was 53°C (127°F) while that for the Row D receptacles (table 5) was 51°C (124°F). None of the receptacles in Rows C and D exhibited overheating during the test.

Table 6 is a summary of the data in tables 2-5. It can be seen in table 6 that all the receptacles which exhibited overheating were wired with aluminum. However, replicate test specimens did not necessarily yield replicate results as noted in the footnotes to table 6. A possible explanation for the lack of agreement among replicate receptacles stems from the use of screw torque as a measure of screw head/wire/contact plate tightness and, hence, contact area and pressure. Torque may not be a good measure of contact pressure, especially at low torque values, because frictional forces, such as those between the screw threads and the contact plate, are included in the measured torque. Also, if the wire loop is not planar, the contact area may be different for each terminal even though the torques are equal. There was no attempt in these experiments to determine if torque measurements resulted in more than approximately equal metal to metal contact areas and pressures.

3.2 Current Cycling Tests with CO/ALR Receptacles

3.2.1 Scope

A test was performed to study the performance of four types of aluminum wired CO/ALR duplex receptacles using the maximum current for which they were rated. The receptacles were subjected to 15 ampere cycles of 3 1/2 hours ON and 1/2 OFF using a 120 volt ac supply.

3.2.2 Procedure

Six specimens of each of four types of CO/ALR receptacles were wired, using 3/4 planar loops, with #10 AWG aluminum non-metallic sheathed cable. The wire was one of the materials commercially available in 1975. A thermocouple was installed on the black wire breakoff tab of each receptacle. A screw torque of 0.138 kg-m (12 lb-in) was applied to each termination point prior to installing each receptacle in a metal box. Resistance measurements were made across the two black wire terminals of each receptacle as illustrated in figure 3. A plastic face plate was installed on each box and the boxes installed in open air on a laboratory bench. The receptacles were wired to a load consisting of 18-100 watt light bulbs. The current load (15 amperes) from the 120 volt, 60 cycle main supply was applied to the receptacles in cycles of 3 1/2 hours ON and 1/2 hour OFF. The breakoff tab temperature was monitored each cycle for the first ten cycles and every tenth cycle thereafter. The temperature was monitored near the end of the ON cycle.

3.2.3 Results and Discussion

The test results are summarized in table 7. The first column designates the four manufacturers of the CO/ALR receptacles tested. The receptacles from Manufacturer 1 contained tin plated components while those from manufacturers 2, 3 and 4 contained either indium plating or a combination of indium and tin plating on plated components. All four types contained brass wire binding screws. The next column in table 7 is a specimen number assigned to each receptacle from each manufacturer. Other columns present the initial resistance as measured across the two black wire terminals (including the breakoff tab) and the breakoff tab temperatures during the first, 30th and 140th ON cycle.

The initial resistances varied from 0.24 to 0.67 milliohms with one exception. One receptacle from Manufacturer 2 (specimen number 3) had an initial resistance of 2.30 milliohms. The breakoff tab temperature of the latter receptacle was consistently higher than that of other receptacles but it did not increase significantly during the period of the test. None of the CO/ALR receptacles exhibited signs of overheating during the test. The breakoff tab temperatures in table 7 cannot be directly compared with those of non-CO/ALR receptacles (tables 2, 3, 4 and 5) because the latter receptacles were tested in an enclosed wall. Thus heat was more easily dissipated from the CO/ALR receptacles than from the non-CO/ALR receptacles.

3.3 Comparison of Initial Termination Point Resistances for CO/ALR and Non-CO/ALR Receptacles

3.3.1 Scope

A series of tests was performed to compare the initial termination point resistances of four types of CO/ALR receptacles with that of two types of non-CO/ALR receptacles. The resistances were measured on newly made terminals that had not been subjected to current cycles.

3.3.2 Procedure

Specimens of four types of CO/ALR and two types of non-CO/ALR duplex receptacles were wired to #10 AWG aluminum and #12 AWG copper non-metallic sheathed cable at screw torque levels of 0.023, 0.046, 0.069, 0.092, 0.115, 0.138, 0.161, 0.184, 0.207 and 0.230 kg-m (2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 lb-in). The aluminum wire and the CO/ALR receptacles were the same types used in the cyclic test described in 3.2. The non-CO/ALR receptacles were the same types used in the test described in 3.1. One receptacle of each type was used with copper wire and a duplicate receptacle of each type was used with aluminum wire.

The procedure used was to insert a 3/4, planar wire loop under the screw heads, tighten to 0.023 kg-m (2 lb-in) screw torque and measure the voltage drop across the two black wire terminals using a 10 ampere load. The probes were located at points A and B as shown in figure 3. The resistance calculated from the measurements included the breakoff tab resistance. The screws were then tightened to 0.046 kg-m and the resistance measured as before. This procedure was repeated for each torque level.

3.3.3 Results and Discussion

The results of the test series with CO/ALR receptacles are presented in table 8. Table 9 includes the results with non-CO/ALR receptacles. The data in table 8 show that the resistances measured across newly made termination points of all four types of CO/ALR receptacles are relatively independent of screw torque. Table 8 data also show that the resistances do not vary greatly with the type of wire. The resistances presented in table 9 for non-CO/ALR receptacles are somewhat more dependent on screw torque. The data in Table 9 also indicate that the resistance of aluminum terminations at low screw torque is higher than that of copper terminations at the same screw torque. For the non-CO/ALR Type 1 receptacle, aluminum and copper yield approximately the same resistances at screw torques of 0.138 kg-m (12 lb-in) and greater. The resistance of aluminum and copper terminations to the Type 2 non-CO/ALR receptacle are approximately equal at torques of 0.207 kg-m (18 lb-in) and greater.

During the tests, it was observed that tightening the wire binding screws of the CO/ALR receptacles in excess of 0.161-0.184 kg-m (14-16 lb-in) occasionally resulted in either buckling of the contact plate or stripping of the screw threads. The fact that CO/ALR termination point resistance is relatively independent of screw torque, as shown in table 8, indicates that it is not necessary to torque the screws above about 0.138 kg-m (12 lb-in) to achieve the minimum initial resistance.

3.4 Measurement of Breakoff Tab Resistance

3.4.1 Scope

The resistances reported in tables 8 and 9 include the resistance of two black wire terminations and the breakoff tab. Measurements were made in order to determine the magnitude of the breakoff tab contribution to the total measured resistance.

3.4.2 Procedure

Duplicate specimens of six types of duplex receptacles were selected for the test. The specimens included two types of non-CO/ALR and four types of CO/ALR receptacles. The non-CO/ALR receptacles were the same types described in 3.1, while the CO/ALR receptacles were the same types described in 3.2 and for which data are presented in tables 7 and 8. One specimen of each type was wired with #12 AWG copper non-metallic sheathed cable and the other specimen with #10 AWG aluminum non-metallic sheathed cable. The wire binding screws were tightened to 0.138 kg-m (12 lb-in) torque. A current of 10 amperes was passed through the receptacles and the voltage drop measured on both the black and white wire sides. Measurements were made from points A to C and A to D as shown in figure 8.

The resistance calculated from the A-C measurement is indicative of the termination point resistance. The A-D measurement includes the termination point resistance, the breakoff tab resistance and the contact plate resistance between the termination point and the breakoff tab. The latter resistance was asssumed to be negligible for the purpose of this experiment. The breakoff tab resistance was obtained by subtracting the A-C resistance from the A-D resistance.

3.4.3 Results and Discussion

The test results are summarized in table 10. The numbers assigned to the CO/ALR receptacles are the same as used in tables 7 and 8. The non-CO/ALR receptacle numbers are the same as those in table 9.

The data in table 10 show that the breakoff tab resistance varies with the type of receptacle and, when the wire to connector resistances are low, it can provide a substantial contribution to the resistance across a receptacle. The Type 2 CO/ALR receptacle had the lowest breakoff tab resistance while the Type 2 non-CO/ALR had the highest. In each case, the breakoff tab resistance is higher than the initial termination point resistance.

The resistance of the breakoff tab is dependent largely upon its design. Thus it varies for each different type of receptacle. In addition, its resistance can vary with different specimens of the same type. For example, the black wire breakoff tabs of the two Type 4 CO/ALR receptacles (table 10) had resistances of 0.274 and 0.341 milliohms.

4. CONCLUSIONS

As mentioned in Section 1.2 of this report, the aluminum alloys used in the laboratory tests of this study were of the post-1972 type. Since pre-1972 wiring was not available for test, the conclusions must be limited to the materials tested.

The data obtained in the laboratory tests described in Sections 3.1 and 3.2 indicate that lack of termination point tightness is a major factor contributing to overheating. For example, the data in tables 2 and 3 show that overheating (defined as a 10°C temperature rise above the average breakoff tab temperature during the third cycle) occurred primarily in receptacles with very low screw torque levels. The only receptacles that overheated to the point of extensive decomposition were at 0.023 kg-m (2 lb-in) screw torque. The breakoff tab temperature of the one receptacle (aluminum wire/steel screws) at 0.069 kg-m (6 lb-in) that overheated according to our definition increased only 11°C above the average third cycle temperature during 390 cycles in the wall test. Despite the problem encountered in using screw torque as a measure of termination point tightness at a particular torque level, the tightness, and hence the metal to metal contact, can be reasonably assumed to increase progressively from 0.023 to 0.138 kg-m (2 to 12 lb-in) torque. It can be concluded that, by maintaining a screw torque of approximately 0.138 kg-m (12 lb-in), the chance of obtaining overheated termination points is substantially reduced.

The type of wire used is another factor contributing to possible overheating. The data in tables 2-6 show that all instances of overheating occurred in receptacles wired with aluminum while none of the copper wired receptacles overheated. These data indicate that aluminum wired termination points at low screw torque are more susceptible to overheating than those wired with copper. The difference in electrical conductivity of the oxide coatings on the two wires may contribute to this. Aluminum oxide is less conductive than copper oxide. Thus, it is more important to obtain good metal to metal contact (by applying higher screw torques) with aluminum than with copper wire.

The decomposition of poly(vinyl chloride) (PVC) wire insulation is another factor that may contribute to overheating. It is not known if traces of PVC which remain on the wire after stripping the insulation contribute to the initial overheating. It is also uncertain if traces of PVC decomposition products which may be expelled by prolonged exposure to normal operating temperatures contribute to initial overheating. Previous studies using thermogravimetric analysis have shown that the plasticizer component of some specimens of PVC can be lost at temperatures of 85°C. PVC degradation resulting from long exposures to lower temperatures was not studied. The scanning electron microscopy and x-ray studies of components of overheated terminals, however, have shown that large quantities of chloride are present at component interfaces. The resultant products could contribute to the corrosion of termination point interfaces.

The comparison of initial resistances across newly made terminations of CO/ALR and non-CO/ALR receptacles (tables 8 and 9) indicate that CO/ALR receptacles provide terminations with lower resistance, particularly at the lower torque levels. The initial resistance is important because the lower the resistance the lower the termination point temperature. Higher temperatures could result in more rapid termination point changes which could enhance degradation with time. The termination point resistances at 0.138 kg-m (12 lb-in) included in table 10 show that the initial resistances of aluminum wired terminations of CO/ALR receptacles are lower than those of non-CO/ALR receptacles. The table 10 values for copper wired terminals show that the resistances of CO/ALR terminations are less than or equal to those of non-CO/ALR terminations. The results obtained in this study and those from previous studies (3) indicate that terminations of lower resistance can be made with CO/ALR receptacles than with non-CO/ALR receptacles. In addition, CO/ALR receptacles are designed with wire restraints to help hold the wire loop under the wire binding screw head. Although laboratory and field data are not yet available to ensure the satisfactory performance of CO/ALR receptacles and switches for long periods of time, i.e., 10-20 years, it can be concluded based on the results of this study and those of other studies [2, 3, 6] that CO/ALR devices provide improved termination points over those made with non-CO/ALR devices.

5. GUIDELINES FOR THE USE OF ALUMINUM BRANCH CIRCUIT WIRING IN MILITARY BUILDINGS

One of the objectives of the study has been to provide the Tri-Services Committee on Building Materials with guidelines for the use of aluminum branch circuit wiring in military buildings. The guidelines presented in this Section are based upon the knowledge available at this time. However, the data limitations resulting from testing only post-1972 aluminum alloys must be kept in mind.

The guidelines for the use of aluminum branch circuit wiring are as follows:

1. For aluminum branch circuit wiring in new installations, Underwriters' Laboratories, Inc. (UL) recommends that CO/ALR rated receptacles and switches be used. It is suggested that this UL recommendation be followed. It is also suggested that the wire binding screws be tightened to and maintained at 0.127-0.150 kg-m (11-13 lb-in) screw torque.

2. Where the terminals of existing aluminum branch circuit wiring, show signs of possible overheating (such as decomposed connector components, odors from overheated organic materials, receptacle and switch covers that are warm when touched etc.), it is suggested that the overheated receptacles and switches be replaced with CO/ALR wiring devices and that the terminations be made to fresh wire by clipping off any PVC wire insulation that shows deterioration plus 5 to 7 cm (2-3 in) of the old wire and making a new 3/4 loop; it is also suggested that the screw should be tightened to and maintained at a torque of 0.127-0.150 kg-m (11-13 lb-in).

3. Where the terminals of existing aluminum branch circuit wiring, connected to non-CO/ALR receptacles and switches, have NOT shown signs of overheating, it is suggested that the screw torque be checked by an electrician periodically to ensure tightness to 0.127-0.150 kg-m (11-13 lb-in). (Electricians who check screw torque should take precautions to avoid loosening of the screws while reinserting connectors into the metal boxes.) It is also suggested that building occupants be alerted to signs of possible termination point overheating such as odors from overheated organic materials, interference with radio or television, receptacle and switch covers that are warm when touched and flickering lights not due to major appliances. In addition, it is suggested that occupants be given guidelines for having problem terminations repaired. For safety reasons, a qualified electrican should carry out all checks and repairs.

4. Where aluminum branch circuit wiring is terminated to receptacles or switches using techniques such as push or backwiring, it is suggested the devices be replaced with CO/ALR devices. It is further suggested that the new terminations be made by clipping off the old exposed wire, making a 3/4 loop and tightening the screw to a torque of 0.127-0.150 kg-m (11-13 lb-in).

An alternative to suggestion 3, above, would be to replace all non-CO/ALR receptacles and switches with CO/ALR devices (as in suggestion 2), even if they have not shown signs of overheating.

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Figure 1. Arrangement of Non-CO/ALR Duplex Receptacles in a Laboratory Wall Structure

COLUMN NUMBER

	1	2	3	4	5	6	7	8	9
Row A									
Row B									
Row C									
Row D									

Row A - Non-CO/ALR duplex receptacles containing zinc plated steel screws wired to #10 AWG aluminum non-metallic sheathed cable.

Row B - Non-CO/ALR duplex receptacles containing brass screws wired to #10 AWG aluminum non-metallic sheathed cable.

Row C - Non-CO/ALR duplex receptacles containing zinc plated steel screws wired to #12 AWG copper non-metallic sheathed cable.

Row D - Non-CO/ALR duplex receptacles containing brass screws wired to #12 AWG copper non-metallic sheathed cable.

The screw torque levels were as follows:

Columns 1 and 2 - 0.023 kg-m (2 lb-in)

Columns 3, 4 and 5 - 0.069 kg-m (6 lb-in)

Columns 6, 7, 8 and 9 - 0.138 kg-m (12 lb-in).

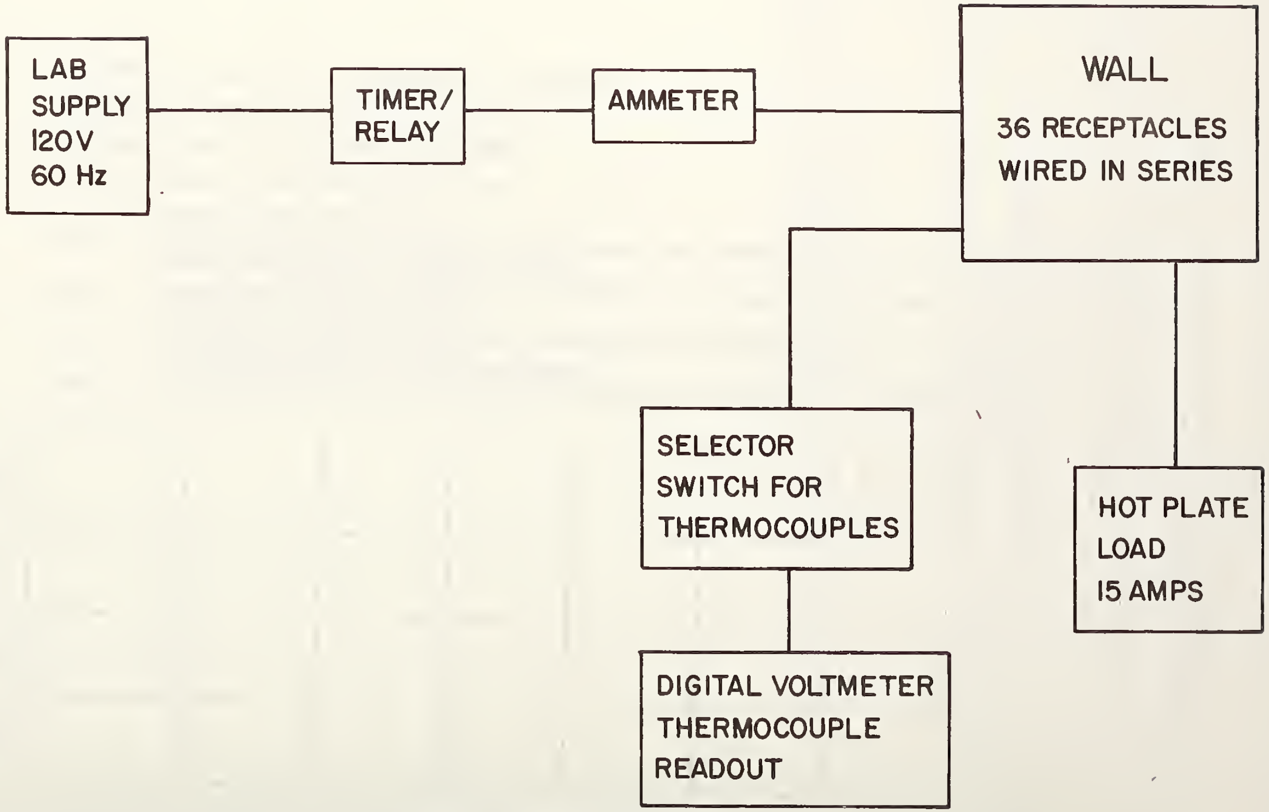

Figure 2. Circuit Diagram of Wall Test

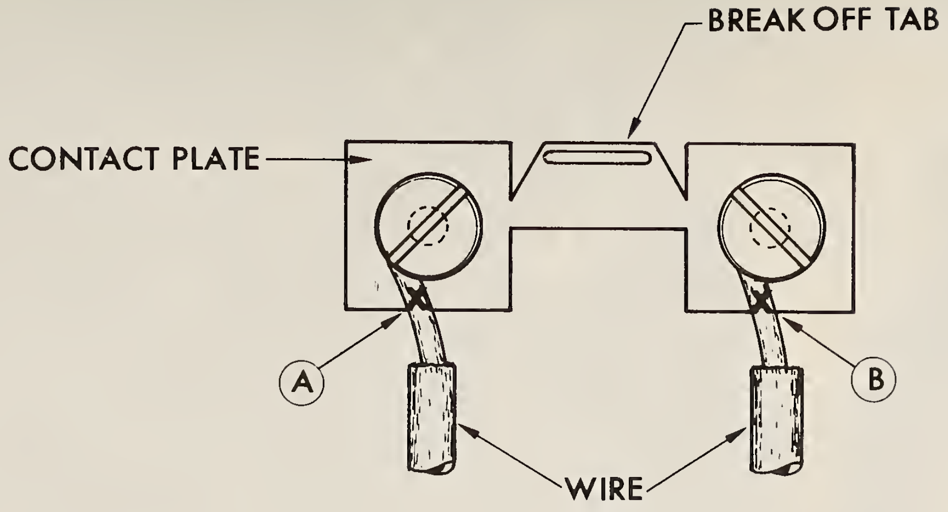

Figure 3. Probe Locations for Measuring Voltage Drops Across Two Termination Points

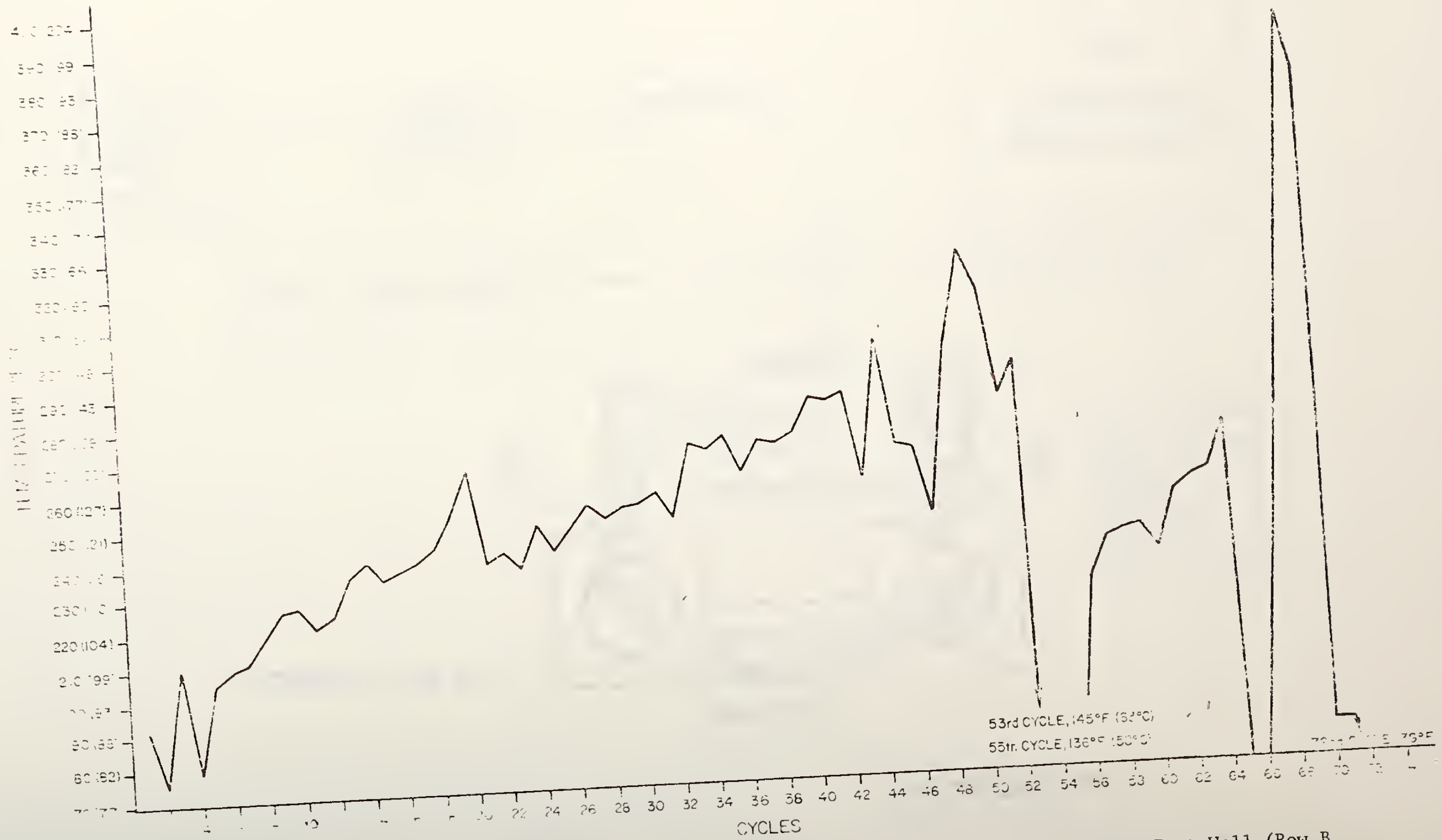

Figure 4. Black Wire Breakoff Tab Temperatures of a Non-CO/ALR Receptacle Installed in the Test Wall (Row B, Column 1, Receptacle 1)

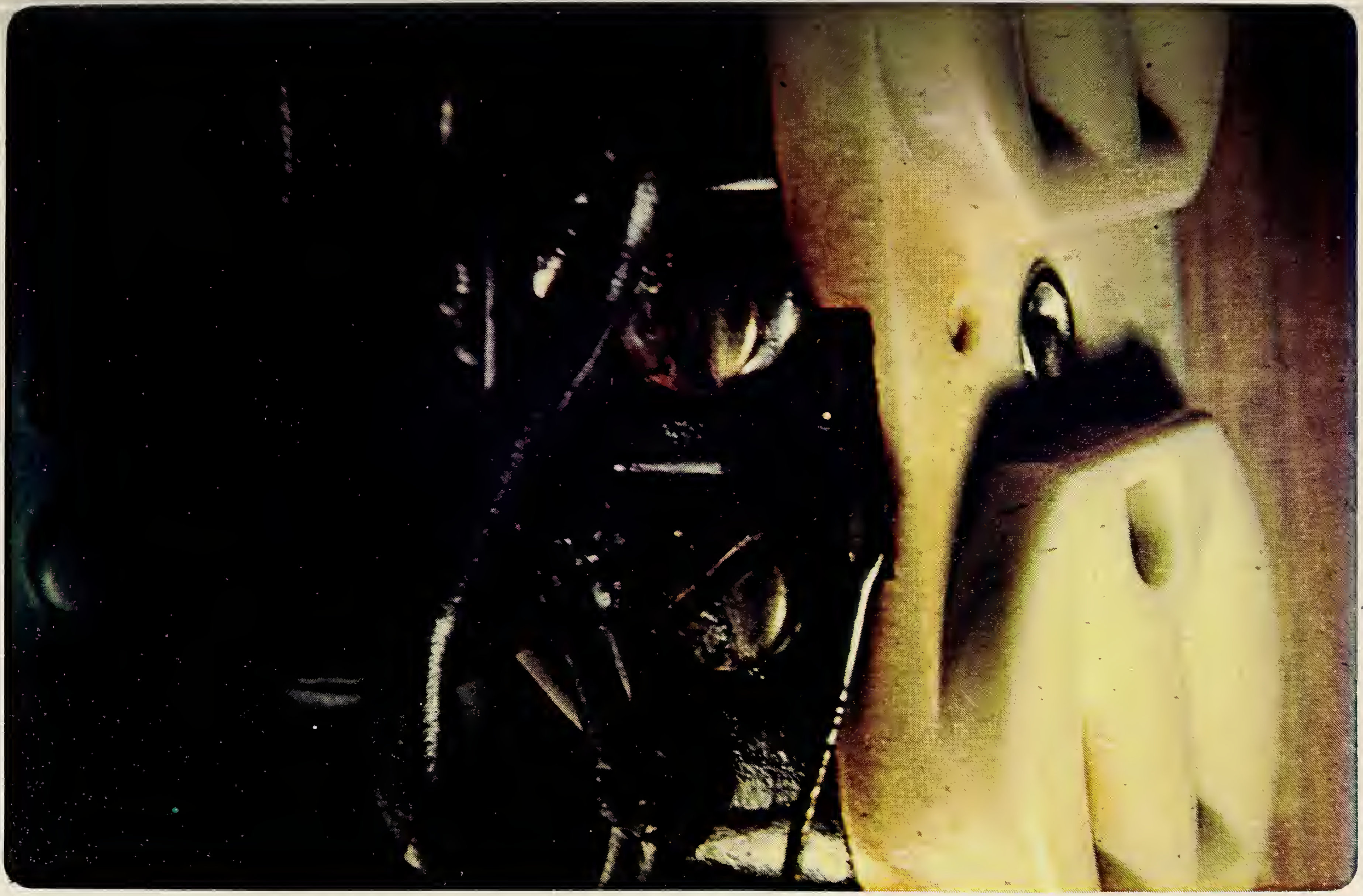

Figure 5. Receptacle 1, Column 1, Row B Before Removal from the Wall Structure.

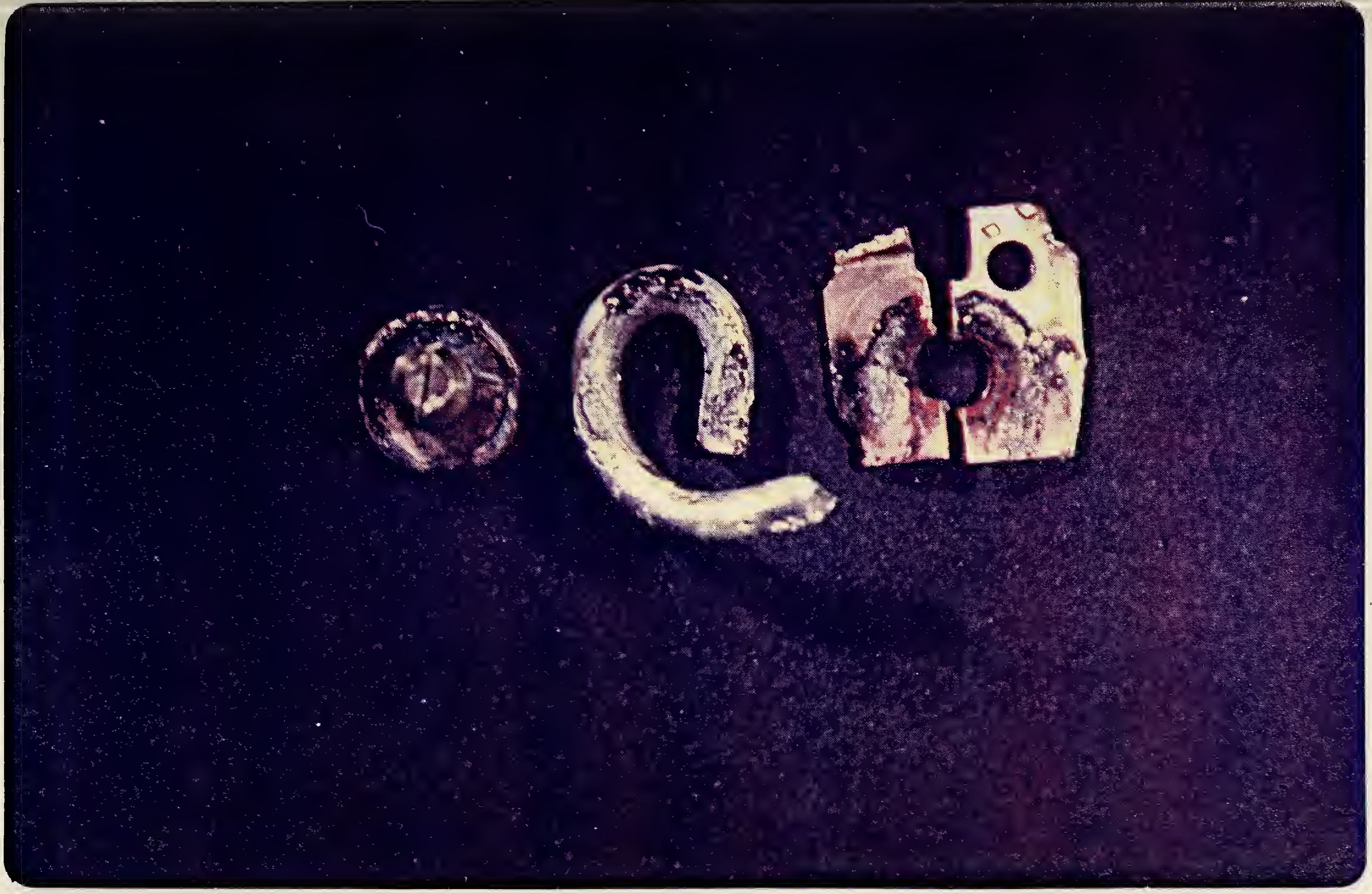

Figure 6. Overheated Termination Point Components from Receptacle 1, Column 1, Row B.

Figure 7. Corrosion of Wire Loop from Receptacle 1, Column 1, Row B.

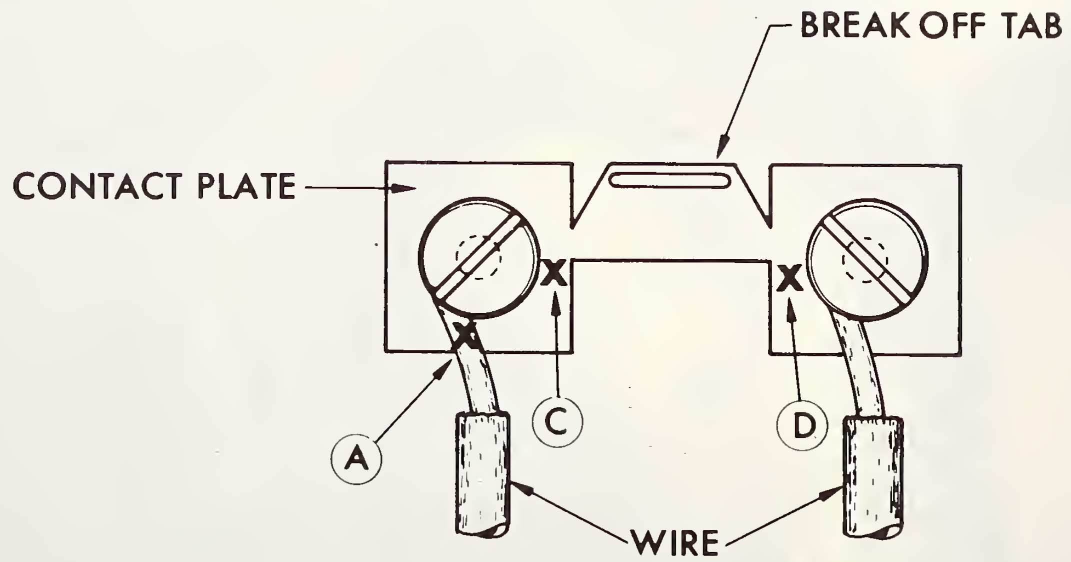

Figure 8. Probe Locations for Measuring Voltage Drops to Determine the Breakoff Tab Resistance.

Table 1. Aluminum Branch Circuit Wiring in Military Residential Units (#6 AWG and smaller)

Military Branch	Name and Location of Base	Type of Wire	Number of Residential Units	Approximate Date of Installation	Performance Observations	Comments
Air Force	Bergstrom AFB, Texas	Aluminum	100	1970	Observed overheating with some receptacles after three months after installation. Estimate that 35% of buildings have had overheated termination points.	Plans are being considered for replacing all receptacles and switches with CO/ALR rated devices.
	Castle AFB, California	Aluminum	250	1971	Performance reported as satisfactory.	
	Davis-Monthan AFB, Arizona	Aluminum	300	1970	Numerous overheating problems.	Copper pigtail retrofit and repair project being developed.
	Ent-Peterson AFB, Colorado	Aluminum	40	1966	Minor problems.	Kitchen circuits are copper wired. Copper pigtail retrofit project in process for aluminum terminations.
	Homestead AFB, Florida	Aluminum	200	1972	Observed overheating with some receptacles about 2 years after installation. Problems primarily with receptacles on kitchen circuits. Estimate that 20% of buildings have had overheated termination points.	Have replaced overheated devices with CO/ALR devices.

Table 1. Aluminum Branch Circuit Wiring in Military Residential Units (#6 AWG and smaller) (cont.)

Military Branch	Name and Location of Base	Type of Wire	Number of Residential Units	Approximate Date of Installation	Performance Observations	Comments
	Homestead AFB, Florida (cont.)	Copper clad aluminum	160	1974	No observed overheating.	
	Langley AFB, Virginia	Aluminum and copper clad aluminum	500	1973-1975	Observed overheating with some aluminum wired receptacles about two months after installation. Primarily on stove, refrigerator and water heater circuits. Estimate that 5% of buildings have had overheated termination points.	Both solid and standard aluminum wire used in kitchen and water heater circuits. Copper clad aluminum used in lighting and other circuits. Lighting fixtures were equipped with copper pigtails. Have replaced overheated devices as needed.
	Nellis AFB, Nevada	Aluminum	300	1970	Minor problems.	Copper pigtail retrofit project planned.
		Aluminum	200	1974	No reported problems.	CO/ALR devices used.
	Wright-Patterson AFB, Ohio	Aluminum	300	1971	Observed overheating with 20-30 receptacles and switches within three years of installation date. One fire reported (started in the stove wiring). Estimate that 10% of buildings have had overheated termination points.	Retrofitted all 300 homes with CO/ALR devices. Retrofitting completed in September 1975.

Table 1. Aluminum Branch Circuit Wiring in Military Residential Units (#6 AWG and smaller) (cont.)

Military Branch	Name and Location of Base	Type of Wire	Number of Residential Units	Approximate Date of Installation	Performance Observations	Comments
Army	Fort Huachuca, Arizona	Aluminum	200	?	Minor problems.	Army personnel have proposed retrofitting devices with CO/ALR devices.
	Fort Meade, Maryland	Aluminum	250	1970	Minor problems.	Army personnel have proposed retrofitting devices with CO/ALR devices.
Navy	Naval Air Station Patuxent River, Maryland	Aluminum	302 (apartments)	?		#8 AWG aluminum used for dryer circuits only.
	Naval Support Activity, Seattle, Washington	Aluminum	1	?	Some overheating at termination points has been observed in the Navy unit but it has not been possible to obtain specific data. Navy personnel attribute overheating to loose connections.	
	Murphy Canyon Heights, San Diego, California	Aluminum	900	?		
	Naval Air Station, Whiting Field, Florida	Aluminum	100	?		

Table 2. Wall Structure Test Results for Non-CO/ALR Receptacles with Steel Wire Binding Screws Wired with Aluminum (Row A Receptacles)[1/]

Column Number	Receptacle Number	Torque (kg-m)	Breakoff Tab Temperature During Third Cycle[2/] °C	Maximum Breakoff Tab Temperature Observed °C	Number of Cycles Completed	Cycle on Which Maximum Temperature Occurred
1	1	0.023	58	58	20	3
	2	0.023	52	59	650	330
2	1	0.023	55	56	280	240
	2	0.023	60	110[3/]	390	210
3	1	0.069	56	56	20	3
	2	0.069	51	57	650	480
4	1	0.069	55	58	280	73
	2	0.069	60	66[4/]	390	210
5	1	0.069	53	56	670	73
6	1	0.138	55	55	20	3
	2	0.138	51	58	650	330
7	1	0.138	55	58	670	500
8	1	0.138	53	57	670	500
9	1	0.138	54	57	670	500

1/ Ambient air temperature around wall was 24 ± 1°C (76 ± 2°F).

2/ For thermocouples installed on black wire side.

3/ After 319 cycles, a thermocouple was added to the white wire breakoff tab. The temperature on the 320th cycle was 88°C. It remained relatively constant through the 390th cycle.

4/ After 309 cycles, a thermocouple was added to the white wire breakoff tab. The temperature on the 310th cycle was 67°C. It remained relatively constant through the 390th cycle.

Table 3. Wall Structure Test Results for Non-CO/ALR Receptacles with Brass Wire Binding Screws Wired with Aluminum (Row B Receptacles)1/

Column Number	Receptacle Number	Torque (kg-m)	Breakoff Tab Temperature During Third Cycle2/ °C	Maximum Breakoff Tab Temperature Observed °C	Number of Cycles Completed	Cycle on Which Maximum Temperature Occurred
1	1	0.023	99	199	280	68
	2	0.023	78	88	110	78, 90
	3	0.023	59	101	60	60
	4	0.023	64	80	220	78
2	1	0.023	61	61	20	1, 14
	2	0.023	51	55	650	53
3	1	0.069	56	56	20	3
	2	0.069	51	56	650	480
4	1	0.069	55	57	280	73
	2	0.069	51	58	390	210
5	1	0.069	53	56	670	500
6	1	0.138	56	56	20	3
	2	0.138	50	54	650	480
7	1	0.138	56	58	670	500
8	1	0.138	55	58	670	500
9	1	0.138	55	57	670	500

1/ Ambient air temperature around wall was 24 ± 1°C (76 ± 2°F).

2/ For thermocouples installed on black wire side.

Table 4. Wall Structure Test Results for Non-CO/ALR Receptacles with Steel Wire Binding Screws Wired with Copper (Row C Receptacles)[1]

Column Number	Receptacle Number	Torque (kg-m)	Breakoff Tab Temperature During Third Cycle[2] °C	Maximum Breakoff Tab Temperature Observed °C	Number of Cycles Completed	Cycle on Which Maximum Temperature Occurred
1	1	0.023	54	54	20	3
	2	0.023	51	57	650	480
2	1	0.023	54	55	280	90
	2	0.023	54	57	380	210
3	1	0.069	54	54	20	3
	2	0.069	49	54	650	480
4	1	0.069	53	55	670	500
5	1	0.069	52	54	670	500
6	1	0.138	54	54	20	3
	2	0.138	49	54	650	480
7	1	0.138	54	54	280	3
	2	0.138	52	54	380	60
8	1	0.138	53	54	670	500
9	1	0.138	52	54	670	500

1/ Ambient air temperature around wall was 24 ± 1°C (76 ± 2°F).

2/ For thermocouples installed on black wire side.

Table 5. Wall Structure Test Results for Non-CO/ALR Receptacles with Brass Wire Binding Screws Wired with Copper (Row D Receptacles)[1/]

Column Number	Receptacle Number	Torque (kg-m)	Breakoff Tab Temperature During Third Cycle[2/] °C	Maximum Breakoff Tab Temperature Observed °C	Number of Cycles Completed	Cycle on Which Maximum Temperature Occurred
1	1	0.023	54	54	20	3
	2	0.023	48	52	650	480
2	1	0.023	54	54	280	3
	2	0.023	49	53	380	210
3	1	0.069	51	51	20	3
	2	0.069	48	53	650	480
4	1	0.069	54	56	670	500
5	1	0.069	54	56	670	50
6	1	0.138	54	54	20	3
	2	0.138	49	52	650	480
7	1	0.138	53	53	280	3
	2	0.138	47	49	380	60
8	1	0.138	52	54	670	500
9	1	0.138	48	52	670	500

1/ Ambient air temperature around wall was 24 ± 1°C (76 ± 2°F).

2/ For thermocouples installed on black wire side.

Table 6. Summary of Observations on the Performance of Non-CO/ALR Electrical Terminations in the Wall Structure

Screw Torque (kg-m)1/	Screw Composition	Type of Wire #12 AWG Copper	Type of Wire #10 AWG Aluminum
0.023	Brass	No overheating	Overheating2/
	Steel	No overheating	Overheating3/
0.069	Brass	No overheating	No overheating
	Steel	No overheating	Overheating4/
0.138	Brass	No overheating	No overheating
	Steel	No overheating	No overheating

1/ 1 lb-in = 1.15×10^{-2} kg-m.

2/ Overheating observed on 4 of 6 receptacles tested.

3/ Overheating observed on 1 of 4 receptacles tested.

4/ Overheating observed on 1 of 5 receptacles tested.

Table 7. Results of Cyclic Tests of CO/ALR Receptacles from Four Manufacturers

CO/ALR Manufacturer	Specimen Number	Initial Resistance (milliohms)	Breakoff Tab Temperatures First Cycle °C	30th Cycle °C	140th Cycle °C
1	1	0.40	31	32	33
	2	0.40	32	32	34
	3	0.41	32	32	34
	4	0.36	32	33	34
	5	0.35	33	33	35
	6	0.38	33	34	36
2	1	0.24	34	36	37
	2	0.26	33	34	36
	3	2.30	44	44	46
	4	0.29	33	33	34
	5	0.35	33	33	34
	6	0.30	32	32	33
3	1	0.49	33	33	34
	2	0.46	34	33	34
	3	0.55	33	34	34
	4	0.49	33	33	34
	5	0.67	36	36	37
	6	0.55	35	36	37
4	1	0.51	37	38	37
	2	0.54	36	38	36
	3	0.54	34	37	34
	4	0.56	36	37	34
	5	0.54	34	37	34
	6	0.52	34	36	34

Table 8. Effect of Applied Torque on Resistances Across Newly Made Terminations Points of CO/ALR Duplex Receptacles from Four Manufacturers[1/]

	Resistances (milliohms) for CO/ALR Receptacle Type							
	1		2		3		4	
Screw Torque (kg-m)[2/]	Aluminum Wired	Copper Wired	Aluminum Wired	Copper Wired	Aluminum Wired	Copper Wired	Aluminum Wired	Copper Wired
0.023	0.35	0.26	0.27	0.22	0.51	0.47	0.65	0.64
0.046	0.30	0.24	0.27	0.22	0.48	0.46	0.60	0.63
0.069	0.27	0.23	0.26	0.21	0.46	0.46	0.57	0.61
0.092	0.27	0.23	0.27	0.21	0.46	0.45	0.55	0.60
0.115	0.26	0.23	0.25	0.21	0.46	0.45	0.55	0.60
0.138	0.26	0.23	0.25	0.21	0.46	0.45	0.54	0.60
0.161	0.26	0.23	0.25	0.21	0.46	0.44	0.54	0.60
0.184	0.25	0.22	0.25	0.24	0.45	0.44	0.54	0.60
0.207	0.24	0.21	0.25	0.24	0.45	0.44	0.54	0.60
0.230[3/]	--	--	--	--	0.45	0.44	0.54	0.60

1/ Resistances include breakoff tab and two wire/connector terminations.

2/ 1 lb-in = 1.15 x 10^{-2} kg-m.

3/ Receptacles for which resistance measurements are not included at 20 lb-in exhibited either screw thread stripping or contact plate buckling.

Table 9. Effect of Applied Torque on Resistances Across Newly Made Terminations Points of Non-CO/ALR Duplex Receptacles[1/]

Screw Torque (kg-m)[2/]	Resistances (milliohms) for Non-CO/ALR Receptacle Type 1[3/] Aluminum Wired	1[3/] Copper Wired	2[4/] Aluminum Wired	2[4/] Copper Wired
0.023	1.83	0.83	2.06	1.30
0.046	1.13	0.77	1.56	1.05
0.069	0.88	0.72	1.21	0.89
0.092	0.79	0.69	1.09	0.87
0.115	0.75	0.68	1.02	0.80
0.138	0.71	0.68	0.95	0.73
0.161	0.67	0.66	0.86	0.69
0.184	0.65	0.64	0.81	0.68
0.207	0.62	0.70[5/]	0.68	0.64
0.230	0.60	--	0.64	0.62

1/ Resistances include breakoff tab and 2 wire/connector terminations.

2/ 1 lb-in = 1.15 x 10^{-2} kg-m.

3/ Type 1 receptacle contained brass wire binding screws.

4/ Type 2 receptacle contained steel wire binding screws.

5/ Screws thread stripped at 0.207 kg-m.

Table 10. Calculated Resistances of Breakoff Tabs and Termination Points

Receptacle Type	Type of Wire	Resistance (milliohms)			
		Termination Point 1/		Breakoff Tab 2/	
		Black Wire	White Wire	Black Wire	White Wire
Non-CO/ALR Type 1 (Brass screws)	Aluminum	0.122	0.116	0.326	0.349
	Copper	0.187	0.115	0.319	0.331
Non-CO/ALR Type 2 (Steel screws)	Aluminum	0.222	0.233	0.400	0.392
	Copper	0.108	0.146	0.383	0.390
CO/ALR Type 1	Aluminum	0.049	0.034	0.163	0.162
	Copper	0.043	0.027	0.149	0.139
CO/ALR Type 2	Aluminum	0.086	0.063	0.095	0.107
	Copper	0.071	0.057	0.108	0.107
CO/ALR Type 3	Aluminum	0.111	0.077	0.252	0.259
	Copper	0.108	0.073	0.262	0.265
CO/ALR Type 4	Aluminum	0.114	0.050	0.274	0.364
	Copper	0.029	0.030	0.341	0.353

1/ Calculated from voltage drop as measured from points A to C on Figure 7.

2/ Calculated from voltage drop differences between points A to D and points A to C on Figure 7.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A study was performed to provide the Tri-Services Committee on Building Materials with guidelines regarding the use of aluminum branch circuit wiring in military buildings. The first part of the study consisted of identifying military bases which contain buildings with aluminum wired branch circuits. Personnel at a number of the bases were contacted in order to estimate the extent of observed problems. Laboratory tests were performed on CO/ALR and non-CO/ALR duplex receptacles wired with both aluminum and copper non-metallic sheathed cable. Overheating of aluminum wired termination points was observed with some receptacles in a current cycling test using non-CO/ALR receptacles at screw torque levels of 0.023 and 0.069 kg-m (2 and 6 lb-in). Aluminum wired non-CO/ALR receptacles tested at 0.138 kg-m (12 lb-in) screw torque showed no signs of overheating and copper wired non-CO/ALR receptacles showed no signs of overheating regardless of screw torque.

This report presents the findings of the study and includes guidelines regarding the use of aluminum branch circuit wiring in military buildings.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Aluminum wiring; branch circuits; copper wiring; military buildings.

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