NBSIR 76-1039

Evaluation of Selected Connectors for Aluminum Wire in Residential Structures

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Institute for Applied Technology
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Prepared for
Consumer Product Safety Commission
5401 Westbard Avenue
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U.S. DEPARTMENT OF COMMERCE, Elliot L. Richardson, ***Secretary***
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Summary

Systems of connecting aluminum wire for possible use in receptacle outlets and elsewhere in 15 and 20 ampere branch circuits in residences are available as practical alternatives to the presently used mechanisms such as the wire binding screw and the twist-on "wire nut" connector. The alternative systems are based on the principle of high deformation of the wire in the connection to achieve more permanent metal-to-metal fittings and/or wire splice devices of several designs. They involve either crimping the device around the wire or swaging the wire into the device with special tools.

Based on tests, basic connection performance of several high-deformation connectors has been established. The results indicate that certain designs of connectors operate with stability and without dangerously over-heating under accelerated laboratory tests.

The tools, however, to be used to crimp terminals are not only bulky and awkward to use but quite expensive. Moreover, they must be correctly coordinated with the terminals and sizes of wires used. There is danger that a misadjusted or improper tool and/or terminal may be used with particular wire or wires which could result in a poor connection. Some improvements in the design of the assembly tools and in the devices themselves would reduce certain installation difficulties encountered during testing, and certain connectors could be slightly modified to avoid human errors during assembly.

Use of these systems and conformance with established codes and standards does not appear to present major problems.

1. INTRODUCTION

This report describes the results of tests on a variety of terminals and splices to be used primarily with aluminum wire. The tests were performed to evaluate the suitability of these terminals and splices as a potential "fix" for residences with 15 and 20 ampere branch circuits wired with "older technology" aluminum wiring systems*. Of particular importance are those branch circuits employing a combination of "old technology" wire and receptacle devices with steel wire binding screws. This combination is known to be most prone to failure. The use of the terminals and splices described in this report has also been considered as an alternative to present termination methods.

Two techniques of connection were evaluated. The first is a terminal device which is fastened to the end of a wire by a crimping or swaging operation and the tongue of the terminal fastened under the binding screw of a wiring device. See Fig. 1. The second type is a splice which connects one or two aluminum wires to a copper wire "pigtail", which in turn is fastened under the binding screw of a wiring device in the usual manner. See Fig. 2. Each terminal or splice that was evaluated will be referred to throughout this report by a letter which designates the device type as shown in Fig. 3.

Suitability of installed electrical devices in most jurisdictions in this country is evidenced by the listing of a testing laboratory such as Underwriters Laboratories (UL). The manufacturer of devices B, C, D and E has indicated that the UL listing has been or is being obtained for these products.

Most jurisdictions follow the requirements for electrical installations as detailed in the National Electrical Code (NEC). Except for the possible lack of an approval (such as the UL listing) for a device, the general use of the connection devices as described in this report would not involve any known conflicts with the NEC.

Since the binding screws on a wiring device are generally not removable, the original ring-tongue configuration of terminals B & C had to be modified by cutting through a section of the ring to form a J-hook configuration.

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* "Older technology" aluminum wiring system refers to the use of an aluminum conductor which does not meet the Underwriters Laboratories (UL) requirements for solid aluminum wires which became effective May 1, 1971 and/or the use of outlet wire terminal devices not rated CO/ALR.

In accordance with the requests of the Consumer Product Safety Commission (CPSC) the following tests were performed on each of the devices where applicable:

1. Heat cycling test
2. Interface photomicrography
3. Mechanical tests
4. Bend tests

Although an evaluation of constriction resistance was requested by CPSC, early investigation showed that comparative evaluation of constriction resistance of crimp and screw connections was not feasible within the scope of this project, and therefore not undertaken. This was indicated in our proposal of laboratory tests.

2. HEAT CYCLING TESTS - GENERAL

A heat cycling test was performed on all the devices (A thru E). In addition, to provide comparative data, receptacles wired directly (without terminal connectors, i.e., wire wrapped around screw) were subjected to the heat cycling test. Any device which did not pass the heat cycling test was not further evaluated. Also, it was arbitrarily decided to limit the test to approximately 5000 cycles of operation.

The heat cycling test is a form of accelerated aging intended to simulate extended service performance. The test consists of subjecting the connection or terminal device to an overload current which is 2.67 times the rated current of the conductor. Thus, for a 20 ampere rated conductor (No. 10 American Wire Gage (AWG), aluminum) the overload test current is 53 amperes and 40 amperes for a 15 ampere conductor rating (No. 12 AWG, aluminum). The current is cycled "on" for a period of 20 minutes and "off" for a period of 10 minutes. The devices and conductors were tested in the open ambient, that is, they were not enclosed in outlet boxes. Initially and at intervals during the test, temperatures at the connection interface and voltage drops across the connections were measured.

2.1 Heat Cycle test on direct wired receptacles

A total of ten duplex receptacles were wired in a series arrangement that permitted current to pass through each screw terminal of the devices. Five were wired with #10 AWG EC-H19 (older technology) aluminum wire* and five were wired with a new alloy aluminum wire. This configuration resulted in a total of 20 terminations for each type of wire. Each binding head screw was torqued to 6 inch pounds (0.7 newton meter).

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* Wire numbers hereinafter do not have the "AWG" reference, but they continue to represent wire sizes in accordance with the American Wire Gage.

Data was usually taken near the end of the 20 minute "on" cycle and the "on" condition extended until the measurements were completed. This insured thermal equilibrium of the connection during the measurement interval. Since there generally is little thermal resistance between the upper and lower screw heads of a duplex receptacle, temperature data was taken on only one screw head. Voltage drop measurements were made across the two connections at points on the wire located 20 mm from the center of each screw head.

The results of the heat cycle test on receptacles wired directly became evident almost immediately. All of the connections failed in less than 100 cycles with the first failure occurring in 3 cycles. Failure was defined when the temperature increased 125 °C above the temperature of the wire. At temperatures above 300 °C the insulating material of the receptacle begins to smoke and char. Many of the connections were allowed to continue overheating until the insulating material around the screw terminals became completely charred. There was, however, a distinct difference in the failure rate of the connections for the two types of wire. Those wired with EC-H19 aluminum wire failed in an average of 18 cycles, whereas connections made with the new alloy wire failed in an average of 42 cycles. Regardless of this, it is clear that receptacles with steel screws wired with #10 EC-H19 or new alloy aluminum wire fail the heat cycling tests. Although there are still no definite data which indicate that this particular accelerated test can in an absolute sense predict the potential life of a connection in service, it is an accepted industry qualification test procedure and does provide comparative information that allows new termination techniques to be evaluated against known methods of terminations.

2.2 Heat Cycle test on terminal A

Terminal type A was subjected to the same heat cycling test. A rack of 10 receptacles was employed for each type of wire. The terminals were crimped at the ends of both types of #10 aluminum wire and the split tongue of the terminal fastened under the binding screws of the receptacles. Each screw was torqued to 6 inch pounds (0.7 newton meter). The results of the heat cycle tests on terminal A are shown in Table I. The average temperature was obtained by averaging the readings of temperature from 20 screw head terminals. The maximum and minimum values of temperature indicate the extremes. After 443 cycles, the terminals connected to the EC-H19 wire were well on their way to failure. At 490 cycles the entire set had to be removed from test because of the high incidence of failure. Terminals on the new alloy wire began to fail at about 1000 cycles and subsequently the number of failures increased to five at which point the entire set was removed from test at 1410 cycles

Voltage drop measurements taken between various connection interfaces showed that the maximum voltage drop occurred between the wire and the terminal. Thus, all the overheating was due to a failure in the crimp connection. Voltage drop measurements between the terminal body and the receptacle binding screw remained low and relatively constant.

The source voltage in the current cycling test is in the order of a few volts, hence, when terminations begin to fail, the current in the series group of devices under test will decrease. The current is initially adjusted for the test value and regulated manually. However, when a connection begins to fail the increased voltage drop causes the current to decrease and therefore the source voltage must be readjusted to obtain the original test current. Finally as more and more connectors fail, manual regulation of current becomes difficult to maintain, hence, the test is discontinued.

The manufacturer of terminal A was informed of the high failure rates that were experienced with both types of aluminum wire. An engineer from the company visited the test facility at NBS, examined the crimping tool, and measured the crimped terminals. He found the crimp tool and terminals to be within specifications, but was unable to offer any explanation for the failures. Thus, based on the failure of terminal A to pass the heat cycle test, no further tests were made except that photomicrographs of the crimped cross section were examined.

2.3 Heat Cycle test on terminals B & C

Terminals B & C were subjected to the same heat cycling tests as terminal A and measurements made in the same manner. A rack of ten receptacles was used to test each terminal type with both types of wire. This resulted in 20 terminations for each terminal type and wire type. The results of the data are shown in Table II. From cycle one to cycle 5080 (when the test was stopped) the temperature data indicates that both terminals are remarkably stable. There are no excessive temperature rises or wide fluctuations indicative of failure. The average was computed from the individual temperature readings for a given terminal and wire type. The minimum and maximum temperatures indicate the extremes of the individual readings. There is a slight increase in temperature from the first cycle, but thereafter the temperature remains relatively constant. Terminal C in which the wire is swaged into an undercut slot on the terminal body operates 15 to 18 degrees higher than terminal B which is a crimp type. This difference can be attributed to the fact that the wire to terminal resistance for terminal C is approximately 50% greater than for terminal B. Typically the resistance from the wire to the terminal body is

60 microohms for the B terminal and 90 microohms for the C terminal. This difference in resistance, however, is small in relation to the total resistance of the connection at the duplex receptacle.

2.4 Heat Cycle test on Splices D & E

Splice type D, which is an in-line splice, is designed for a range of circular mil area (CMA) which permits two #12 aluminum and one #14 copper wire to be crimped together in parallel. A total of ten splices were arranged in a series configuration so that five devices provided a current path from one aluminum conductor to the other and five devices provided a current from the aluminum wire to the copper wire. Splice type D was tested only with the #12 new alloy aluminum wire because #12 EC-H19 wire was not available for the test. Table III shows the results of the heat cycle test on splice D. There are no excessive temperature rises or wide fluctuations indicative of failure. The voltage drop across the splice averaged 0.0077 volts after 5000 cycles which for the 40 ampere test current results in an average resistance of 0.19 milliohms.

Splice E is a two-crimp butt splice with an aluminum wire CMA range of 13100 to 20800 and a copper CMA range of 5130 to 13100. This splice was chosen to splice together two #10 aluminum wires and one #12 copper wire. Although the maximum CMA range for aluminum would allow two #10 wires to be inserted in one end of the splice, this was not physically possible because the inside diameter of the splice was insufficient to accept two #10 wires. The only configuration possible was to place one #10 aluminum and one #12 copper wire in one end and a single #10 aluminum wire in the other end of the splice. However, a single #10 aluminum wire in one end is smaller than normally recommended by the manufacturer. This exception, according to the manufacturer, was not expected to affect the performance.

For the heat cycle test a total of 20 type E butt splices were arranged in the following manner. Ten splices were used with the EC-H19 wire and ten with the new alloy wire. For each type of wire half the number of devices were wired so that current would pass from one aluminum wire to one copper wire. The results of the heat cycle test on splice E is shown in Table III. Again there are no excessive temperature rises or wide fluctuations over the cycling period. There is a 5 to 7 °C difference between the two types of wire but of more importance is the stability after the first cycle. There was one failure which was evident in the first few cycles of operation. An excessive voltage drop developed between the body of the splice and the single #10 EC-H19 wire. Examination of the splice revealed that the integral perforated metal sleeve was missing from the end that was overheating. A splice with a missing, removable sleeve was unnoticed before crimping. This experience did, however, dramatically demonstrate the functional requirement of the perforated sleeve.

3. INTERFACE PHOTOMICROGRAPHY

Each of the terminals and splices was photomicrographed in order to examine the effectiveness of the wire-connector interfaces. Samples were made with older technology (EC-H19) and new alloy aluminum wire, and in the case of splices a copper wire was included. Each of the samples was sectioned normal to the long axis of the wire and through the long axis of the wire at the wire-terminal interface. Color photography was employed to enhance the contrast of the various metal interfaces. Figures 4 thru 7 are a selected number of photomicrographs of the various terminals and splices chosen to illustrate generally the type of information revealed. Fig. 4 shows a cross section through the crimp on terminal type A with #10 EC-H19 wire. Although the aluminum conductor appears to be in good contact and deformed into the perforations of the wire barrel, this connection failed the heat cycling test. This view does show one possible reason for the failure. Note that the geometry of the formed crimp is such that there is no means for it to retain pressure on the wire after numerous cycles of thermal expansion. It is surmised that the heat cycling causes the wire to expand which in turn may slightly open the crimp and loosen the wire terminal interface. Fig. 5 shows the same device sectioned through the longitudinal axis of the conductor. This view shows that the conductor is deformed to about one half its diameter and extruded into the perforations of the wire barrel. Further investigation would be required to determine the actual cause of failure.

Fig. 6 shows a cross section of device type E which is a butt splice with a #10 EC-H19 aluminum and a #12 copper wire crimped together in the same barrel. This view shows that the aluminum has been extruded through the thin brass liner perforations. This should allow clean aluminum metal to be brought into direct contact with the liner and wire barrel. Note that the copper wire does not appear to extrude into the perforations. It is interesting to note the shape of the outer surface produced by this crimp. The geometry is such that a reverse curved surface is produced on one side with respect to the other side. This tends to lock the crimp and make it act like a spring so that the crimp maintains constant pressure. Figure 7 shows the cross sectional view through the longitudinal axis of the aluminum conductor in one end of the type E splice. This view shows that the crimp has considerably reduced the cross section of the wire and the brass perforated liner appears to be split in the area of greatest deformation. All of the samples employing this type of crimp seemed to have a split liner and occasionally the aluminum conductor would become separated in the region of greatest deformation.

The manufacturer was made aware of these observations but maintained that the electrical interface is not affected. This seems to be verified by the successful heat cycle tests on all terminals and splices employing a brass perforated liner and the reverse curved crimp. Of the five types of devices evaluated, types B, D, and E are supplied by the same manufacturer and employ the same crimp. Terminal C relies on deforming the aluminum wire into an undercut channel on the terminal. The aluminum is apparently wiped clean by the edge of the channel as it is forced in. This is referred to by the manufacturer as a tamp crimp. Examination of its cross section under magnification showed no obvious defects. Most of the contact seems to be at the bottom and bottom sides of the channel.

Generally the photomicrographs revealed no significant difference between the EC-H19 and the new alloy wire. The photomicrograph analysis of the devices in this study did not appear to be particularly useful for prediction of performance in their ultimate use.

4. MECHANICAL TESTS

Axial and right angle load tests were performed on samples of EC-H19 and new alloy wire with and without terminals to determine the tensile strength of the terminal and wire. The tests were made on a tensile testing machine in which the specimen is clamped at one end and pulled from the other end by a moving cross head until a fracture occurs. For axial tests the tongue of the terminal was clamped and for right angle tests the terminal was clamped across the wire barrel near the tongue. The machine records the force and the elongation (i.e. stress/strain). For this test the maximum force required to fracture the sample was reported. In addition, the machine has a variable cross head speed which can be adjusted to accommodate the ductility of the sample. The new alloy aluminum wire is far more ductile than the EC-H19 wire and therefore the cross head speed was selected arbitrarily for each sample type to complete the testing in a reasonable time.

Terminal type A was not tested because it failed the heat cycling test. Only terminals B & C were tested for tensile strength. The results on samples of these terminals showed that in all cases the wire fractured and not the connector. This result coupled with the fact that splice types D & E employ the identical crimp design of terminal B led to the decision not to test types D & E for tensile strength. Furthermore, the bending tests relate more to the actual service performance of these devices than tensile loading tests. The following is a brief description of the results based on the tensile test data shown in Table IV:

1. All of the wire samples tested without connectors (speciments 1 - 10) fractured within the 10-inch gauge length except for specimen no. 8.

Since this specimen fractured outside the guage length, no elongation is reported.

2. Three of the five EC-H19 wire specimens (12, 13, and 15) tested axially with terminal B fractured where the wire entered the terminal. The wire in specimens 11 and 14 fractured at the crimp in the terminal.

3. All the alloy wire specimens (16-20) tested axially with terminal B fractured where the wire entered the terminal.

4. All of the EC-H19 wire specimens (21-25) tested axially with terminal C fractured where the wire entered the terminal.

5. All the alloy wire specimens (26-30) tested axially with terminal C fractured several centimeters from the connector.

6. All of the wire specimens (31-40) tested at right angles to terminal B fractured where the wire entered the terminal. In each case the body of the wire barrel cracked on the back side.

7. Four of the five EC-H19 wire specimens (41-44) tested at right angles to terminal C fractured near the tongue of the terminal. The wire pulled completely out of the terminal in specimen 45.

8. For the alloy wire specimen tested at right angles with terminal C, the wire pulled out in two tests (specimens 46 and 47), one wire fractured about midway in the swage (specimen 48), and two wires fractured near the tongue end of the terminal (specimens 49 and 50).

It is interesting to note from Table IV that the two sets with alloy wire on terminals B & C (specimens 16-20 and 36-40) failed in axial tensile tests at consistently greater loads than alloy wire specimens without terminals.

5. BEND TESTS

Bending tests were performed on wires terminated with terminals or splices to determine their ability to withstand the typical manipulation of the wires in the installation process. Two types of bending tests were performed. The first test consisted of subjecting samples to destructive bend tests. The second test was an investigation of the bending stresses that might occur in a typical installation process. This test provided mostly qualitative information on the problem of retrofitting existing wiring to the terminal or splice approach.

The destructive bend tests on terminal devices were made by fastening the tongue of the terminal under the head of the wire binding screw of a receptacle device and bending the wire through alternating 90 degree bends until failure occurred. The bend was made by holding the wire about 5 cm from the terminal end and pushing the wire in a plane normal to the rotational axis of the screws. In addition, comparative tests were made in the same manner on a typical old style receptacle with the wires connected directly under the binding head screws. The results of the destructive bend tests with and without terminals showed that the following three types of failures occur:

1. wire broke
2. terminal or wire loosened under screw
3. tongue of terminal opened

It was found that often the difference between the wire breaking and the terminal loosening under the screw depended on whether it was the upper or lower screw terminal of a receptacle. This difference is apparently due to the breakoff tab which can interfere with the rotation of the terminal or wire in the loosening direction.

The destructive bend tests for splices was made by clamping the splice, holding the wire at a point about 5 cm from the splice, and bending the wire through alternating 90 degree bends until the wire broke. Each 90 degree excursion is defined as one bend. Table V shows the average number of ninety degree bends required to break the wire. If the terminal did not loosen under the screw, the average number of bends required to break the EC-H19 wire is 3, whereas, direct connection of the wire under the screw head required an average of 5 bends to break the wire. Also, the new alloy wire directly connected under a screw head can withstand more bending than various terminals and splices before breaking. For the terminals and splices which are crimped to the wire, the point of bending usually begins just inside the wire barrel where the constriction of the wire begins. The stress is concentrated at this point whereas a wire under a screw head is not constricted to bend at one point. Of more importance than breaking is the tendency for terminals B & C to loosen under the screw as a result of bending the wire. Terminals B & C have a J-hook tongue configuration which seems to be worse with respect to loosening than direct wiring to the screw terminals. With the J-hook terminals it was not uncommon for the screw to loosen in the first or second bend. Furthermore, the hook tongue on these terminals often opened with a subsequent loosening of the screw. Since there is no means on the receptacle to limit the rotation or restrain the wire, the hook can open up in one direction and loosen the screw in the other direction.

Terminal devices B & C were subjected to a typical retrofitting installation exercise in order to discover the practical problems. It was assumed that the terminals would be used with a typical old style receptacle mounted in a standard 2 x 2 1/2 inch (5 cm x 6.3 cm) steel outlet box with an average length of wire folded in the box behind the receptacle with wires wrapped around the screw terminals. The receptacle was pulled out, the wires cut as close to the receptacle as possible, the wire loops removed, the terminal connected to the ends of the circuit wires, and the tongue of the terminal fastened under the screws. The receptacle was pushed back into the box and fastened. The sides of the box were removed to expose the condition of the wiring. This exercise was repeated several times. The following are typical of the condition of the completed wiring:

1. The body of the terminal, which is not insulated, was often found to be contacting the inside surface of the box. This condition was due primarily to the connector bending outward slightly in the process of pushing the receptacle back in the box. The strength of the terminal tongue is insufficient to prevent it from bending outward.

2. The tongue often became loosened under the screw or opened up as a result of pushing the receptacle back into the box.

3. With the EC-H19 wire there was one instance were the wire broke off at the terminal.

From the conditions cited above it is doubtful that the terminals in their present form would be practical as a "fix" for residences with aluminum branch wiring. In general, more care than conventional wiring techniques is required for these terminals. However, the use of a heavy insulating sleeve which is shrunk over the terminal wire barrel and the wire would probably alleviate the shorting problem and prevent sharp bends of the wire at the terminal. The weakness of the terminal tongue may be due in part to the cutting away of tongue material to form the J-hook configuration.

Splices D & E were also subjected to the same retrofitting installation exercise. Splice D is an in-line crimp splice designed to splice two #12 aluminum and one #14 copper wire together. See Figure 8. Splice E is a butt crimp splice for splicing two #10 aluminum and one #12 copper wire together. The idea with both of these devices is to splice a pair of aluminum wires together with a copper pigtail which in turn is connected to the receptacle device in the normal manner.

The type D splice can be used in two ways; all three wires entering from one end or two wires entering from one end and one from the other. Figures 8 and 9 each show the completed connections of the two possible configurations. There did not seem to be a preferable configuration, except that when all the wires enter one end the manipulation of the wires into the box is similar to the familiar "wire nut" splice. The time required to complete the retrofitting job for each configuration averaged about seven minutes. Much of the time is taken with positioning the wires for crimping and shrinking the insulation over the splice. Figure 10 shows the crimping operation and Figure 11 shows the use of a heat gun to shrink the insulation over the splice. In general there were no problems associated with the type D splice even when a full-sized ground wire is employed. There seemed to be ample room in the box to accommodate up to three splices. It should be mentioned that for this exercise only the new alloy wire was available in the #12 size. It would be expected that wire similar to the EC-H19 characteristics would be more difficult to manipulate and perhaps more care would need to be taken to insure that sharp bends do not occur at the splice. The shrink tubing, if it extends over the wire, is very helpful in preventing sharp bends at the splice.

The crimping tool provided by the manufacturer for splices D and E is pneumatically powered and heavy. It is intended for industrial production where the tool can be supported while the splice with the wires is positioned in the jaws. In a typical field installation the tool was found to be bulky and cumbersome to use because it must be held with one hand while the splice and wires emanating from the box are positioned in the jaws. Many of the field installations would involve receptacle wiring which is located approximately 30 cm above the floor, a position which makes the crimping operation even more awkward. A crimping tool of a different design to overcome the above described objectionable characteristics appears technically feasible. However, despite any improvements that could be made there exists the practical field problems of insuring correctly coordinated tools and terminals with the wire sizes used. There is danger that the improper or misadjusted tool and/or terminal may be used with particular wire or wires which could result in a poor connection.

An additional problem requiring some attention is that the perforated inner sleeve of the splice often has a tendency to be pushed out when inserting the wires. This is particularly so for the type D splice. In some samples the insert had fallen out. As mentioned previously, this was the reason for one failure in the heat cycling test.

The results of subjecting the type E splice to the same retrofitting exercise was less favorable than the type D because the type E is larger. Figure 12 shows the completed splices ready to be installed in the box. The length of the shrink tubing supplied for the type E splice was only the length of the splice. It would be desirable to employ a slightly longer tubing so that it could shrink over the wire. The reason again is to prevent sharp bends at the ends of the splice. Although the splices and wires can be folded into the box and the receptacle mounted in place, the additional volume occupied by the three splices crowds the box and probably would affect the number of allowable conductors in a box as established by the National Electric Code, 1975 (Paragraph 370-6). This may necessitate the use of an outlet box with an extension ring to provide the required volume. If there exists older technology wire with the old sized ground wire (usually two sizes smaller than the current carrying conductors) then the ground conductor could be spliced with the type D in-line splice which is much smaller.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the test results the following are conclusions and recommendations on each of the five terminal devices:

1) Wiring devices with steel screws connected directly to either "new" or "old" technology aluminum wire did not pass the heat cycle test. Although the heat cycle test does not quantify the potential life of a connection in service, it is an accepted industry qualification test procedure and does provide comparative information that allows new termination techniques to be evaluated against known methods of termination.

2) Device A, which is a crimp terminal with a locking-spade tongue, failed the heat cycling test for both old and new technology aluminum wire. The geometry of the crimp is such that there is no means for it to retain the pressure on the conductor. This terminal is <u>not</u> recommended for service with aluminum wire in residential branch circuits.

3) Device B, which is a crimp terminal with the tongue modified into a J-hook configuration, was cycled over 5000 cycles in the heat cycling test without failure or excessive temperature excursions. The tongue of the terminal tends to loosen or open up under the receptacle binding screw as a result of bending the wires into a receptacle box. The weakness of the tongue often permits the body of the terminal to bend outward and cause it to contact the sides of the box. If this terminal is to be used in residential aluminum wiring, it is recommended that an insulating sleeve be positioned over the terminal body and wire, and that care be exercised in the installation to prevent loosening and/or opening of the terminal tongue under the screw.

4) Device C, which is a swage crimp terminal with the tongue modified into a J-hook configuration, was cycled over 5000 cycles in the heat cycling test without failure or excessive temperature excursions. Right angle axial tensile-tests on the wire and

terminal showed that this is its weakest mode, but still quite adequate for its intended use. The tongue of the terminal tends to loosen or open up under the receptacle binding screw as a result of bending the wires into a receptacle box. The weakness of the tongue often permits the body of the terminal to bend outward and cause it to contact the sides of the box. If this terminal is to be used in residential aluminum wiring, it is recommended that an insulating sleeve be positioned over the terminal body and wire, and that care be exercised in the installation to prevent loosening and/or opening of the terminal tongue under the screw.

5) Device D is an in-line crimp splice designed for connecting together two #12 aluminum and one #14 copper wire pigtail which in turn is connected to the wiring device. This splice was cycled over 5000 cycles in the heat cycling test without failure or excessive temperature excursions. The bend and simulated retrofitting tests indicated that there are no serious problems in its use in standard receptacle boxes. The crimping tool provided by the manufacturer, however, is bulky and awkward to use in a field environment. It is recommended that the shrink type insulating sleeve extend over the wires as well as the body of the splice to prevent sharp bends at the wire splice interface.

6) Device E is a butt crimp splice designed for connecting together two #10 aluminum and one #12 copper wire pigtail, which in turn is connected to the wiring device. This splice was cycled over 5000 cycles in the heat cycling test without failure or excessive temperature excursions. This device is much larger than the type D, hence, the additional volume occupied by them creates a marginal situation with respect to the general requirement in the 1975 National Electrical Code, Paragraph 370-6 (Boxes shall be of sufficient size to provide free space for all conductors enclosed in the Box). The crimping tool provided by the manufacturer is bulky and awkward to use in a field environment. It is recommended that the shrink type insulating sleeve extend over the wires as well as the body of the splice to prevent sharp bends at the wire splice interface.

Table I Heat Cycle data for terminal A

Cycle No.	Wire Type	Min. Temp. °C	Max. Temp. °C	Avg. Temp °C
1	#10 EC-H19	80	95	89
443	#10 EC-H19	124	315	188
490	#10 EC-H19	Entire Set Removed From Test		
1	#10 New Alloy	75	86	81
443	#10 New Alloy	83	109	91
1089	#10 New Alloy	82	320	102
1410	#10 New Alloy	Entire Set Removed From Test		

*53 amperes "on" 20 minutes, "off" 10 minutes

Table II Heat Cycle Data for Terminals B & C

Cycle No.	Terminal	Wire Type	Min. Temp °C	Max. Temp °C	Avg. Temp °C
1	B	#10 EC-H19	99	106	102
50	B	#10 EC-H19	103	106	105
417	B	#10 EC-H19	101	110	105
1475	B	#10 EC-H19	96	102	99
5080	B	#10 EC-H19	103	111	107
1	B	#10 New Alloy	96	108	99
50	B	#10 New Alloy	98	110	102
417	B	#10 New Alloy	96	115	103
1475	B	#10 New Alloy	96	107	101
5080	B	#10 New Alloy	96	112	102
1	C	#10 EC-H19	110	128	116
50	C	#10 EC-H19	112	134	119
417	C	#10 EC-H19	111	131	118
1475	C	#10 EC-H19	108	133	116
5080	C	#10 EC-H19	111	137	120
1	C	#10 New Alloy	111	118	113
50	C	#10 New Alloy	110	126	118
417	C	#10 New Alloy	112	129	121
1475	C	#10 New Alloy	110	129	120
5080	C	#10 New Alloy	112	128	121

53 amperes "ON" 20 minutes "OFF" 10 minutes

Table III Heat Cycle Data for Splices D & E

Cycle No.	Splice	Wire Type	Min. Temp °C	Max. Temp °C	Ave. Temp °C
1	D	#12 New Alloy #14 Copper	56	72	63
570	D	" "	61	68	65
3457	D	" "	61	76	66
4642	D	" "	64	74	67
5314	D	" "	64	71	68
1	E	#10 New Alloy #12 Copper	54	72	60
508	E	" "	58	73	64
2272	E	" "	58	73	62
5024	E	" "	59	72	63
1	E	#10 EC-H19 #12 Copper	63	73	67
508	E	" "	58	73	71
2272	E	" "	59	74	70
5024	E	" "	68	74	70

Table IV Results of Tensile Tests of Aluminum Wire and Wire-Terminal Types B & C

Axial tensile tests on wire with no connectors

Specimen	Wire Type	Maximum Load (pounds force)	%Elongation in 10 inches
1	EC-H19	223	2.2
2	EC-H19	226	2.2
3	EC-H19	227	2.2
4	EC-H19	219	1.3
5	EC-H19	228	2.1
6	alloy	126	22.6
7	alloy	125	20.7
8	alloy	126	-
9	alloy	125	22.1
10	alloy	126	23.4

Axial tensile tests on wire with Terminal B on one end

Specimen	Wire Type	Maximum Load (pounds force)
11	EC-H19	193
12	EC-H19	199
13	EC-H19	194
14	EC-H19	189
15	EC-H19	183
16	alloy	134
17	alloy	134
18	alloy	134
19	alloy	131
20	alloy	133

Axial tensile tests on wire with Terminal C on one end, pulled with connector clamped

Specimen	Wire Type	Maximum Load (pounds force)
21	EC-H19	178
22	EC-H19	182
23	EC-H19	180
24	EC-H19	186
25	EC-H19	182
26	alloy	137
27	alloy	135
28	alloy	134
29	alloy	136
30	alloy	135

Table IV continued

Right angle tensile tests on wire with Terminal B on one end

31	EC-H19	116
32	EC-H19	90
33	EC-H19	97
34	EC-H19	132
35	EC-H19	86
36	alloy	113
37	alloy	110
38	alloy	103
39	alloy	86
40	alloy	91

Right angle tensile tests on wire with Terminal C on one end

41	EC-H19	76
42	EC-H19	57
43	EC-H19	72
44	EC-H19	72
45	EC-H19	46
46	alloy	52
47	alloy	68
48	alloy	96
49	alloy	56
50	alloy	62

Cross Head Speads:

EC-H19 Samples .....0.05 inches per minute (1.3 mm per minute)
Alloy Samples ..... 0.2 inches per minute (5 mm per minute)

Table V Destructive Bend Tests on Wires Terminated With Terminals B & C and Splices D & E

Terminal or Splice	Wire Type	Avg. No. of Bends
B	#10 New Alloy	15
C	#10 New Alloy	10
E	#10 New Alloy	11
D	#12 New Alloy	8
Direct Under Screw	#10 New Alloy	18
B	#10 EC-H19	3
C	#10 EC-H19	3
E	#10 EC-H19	3
Direct Under Screw	#10 EC-H19	5

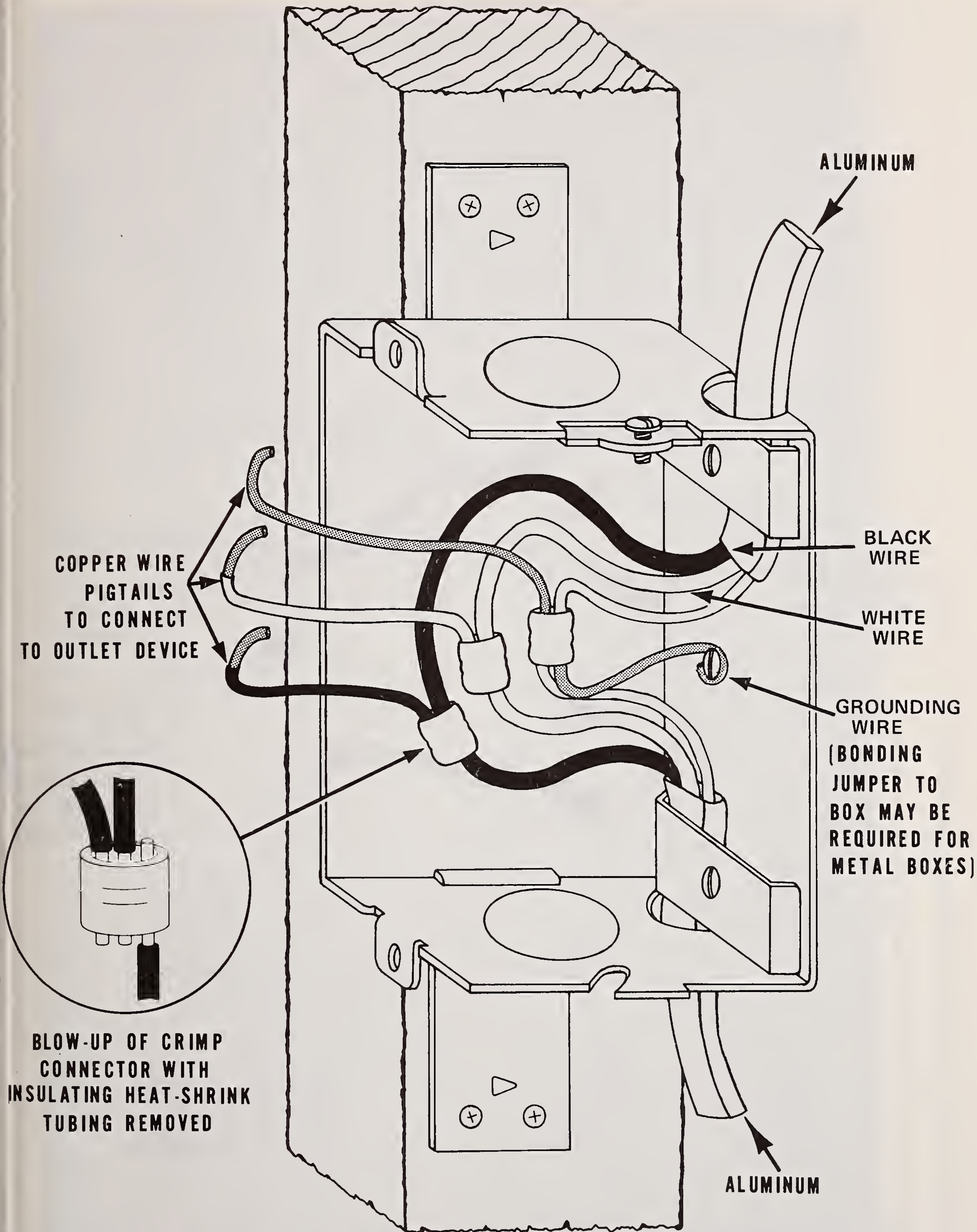

Fig. 2 Splices used to connect aluminum wire to copper wire pigtails which are fastened under the binding screws of a wiring device.

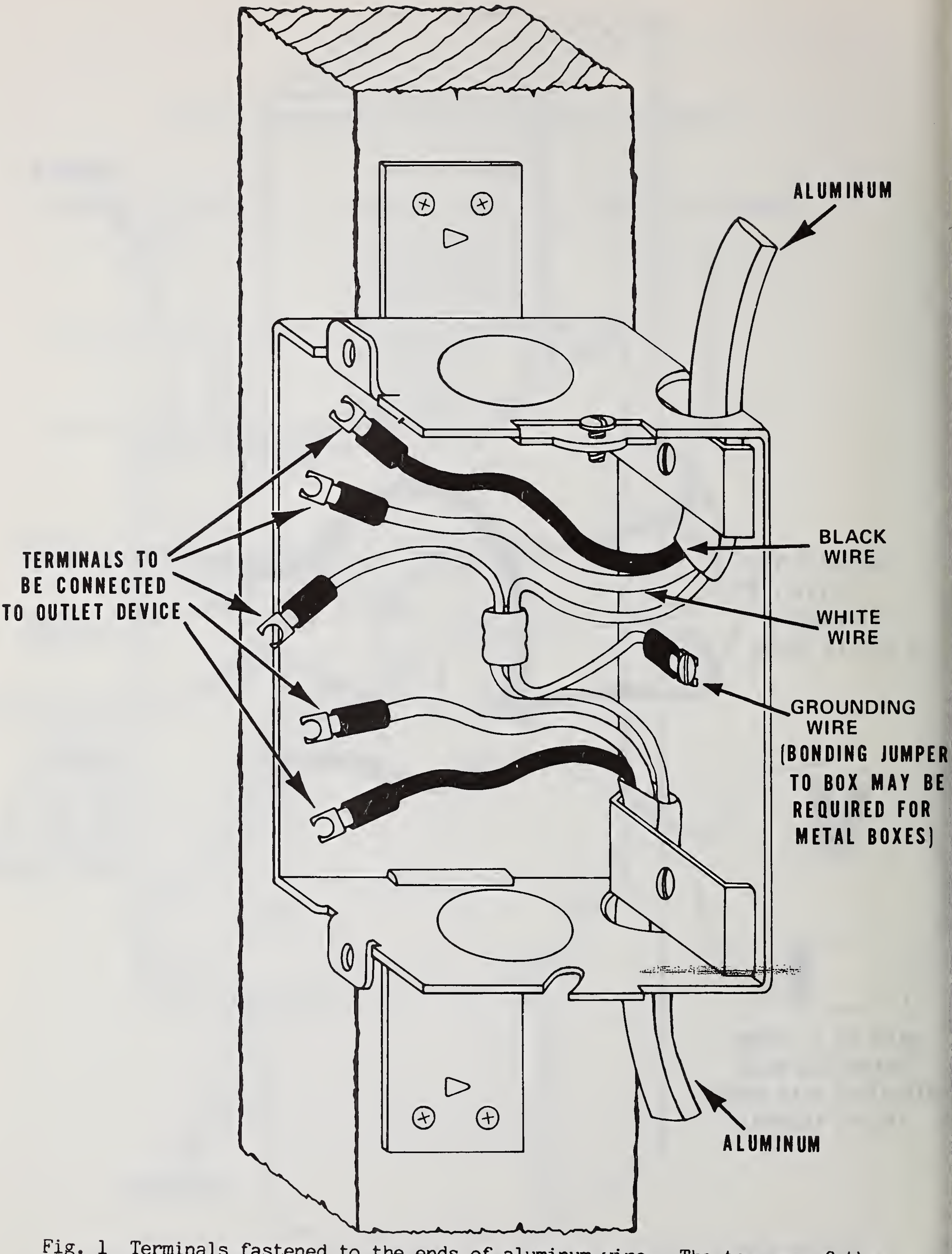

Fig. 1 Terminals fastened to the ends of aluminum wire. The tongues of the terminals are fastened under the binding screws of a wiring device.

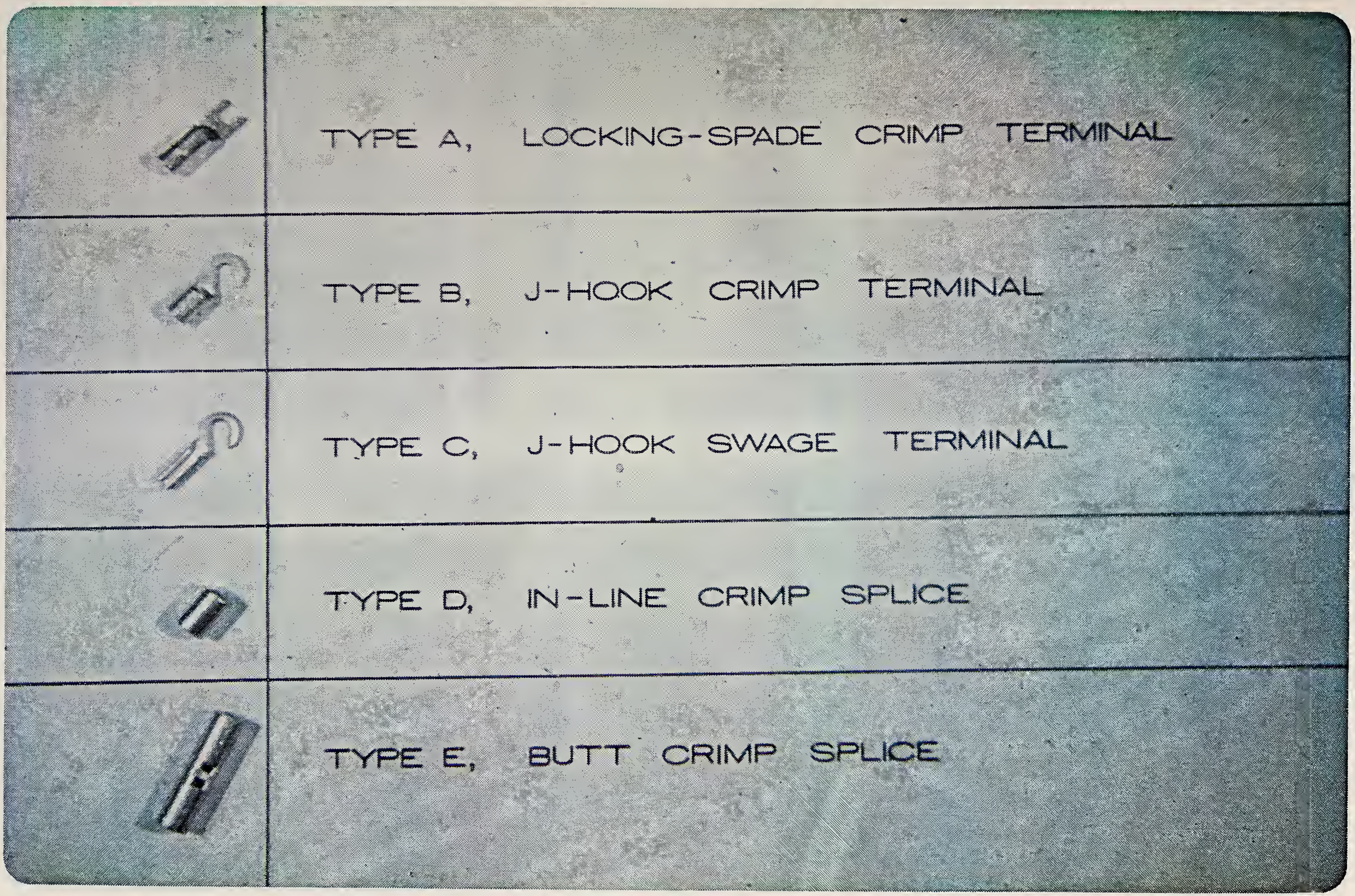

Fig. 3 The five connectors selected for evaluation

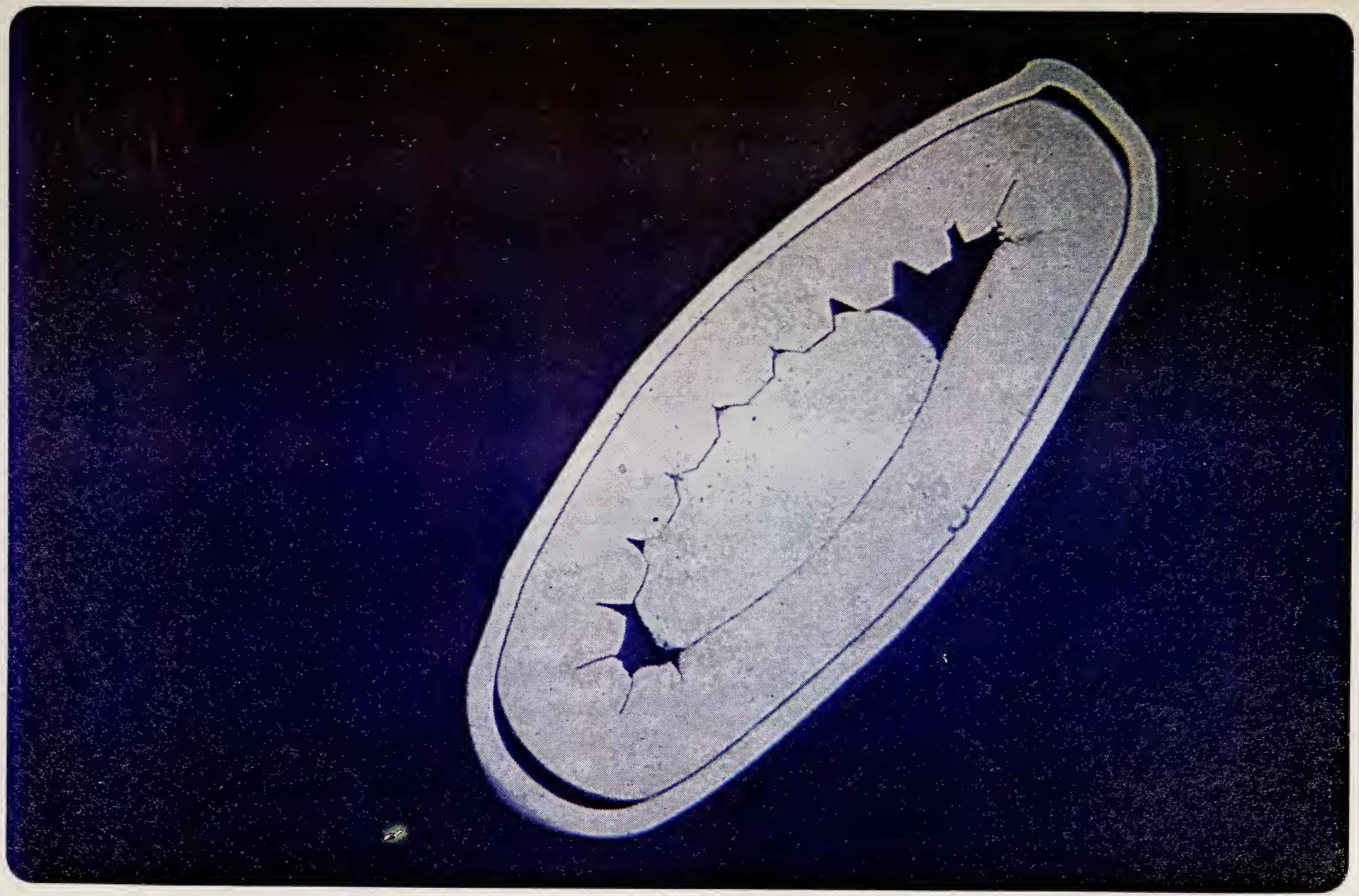

Fig. 4 Cross section through the crimp of Terminal A.

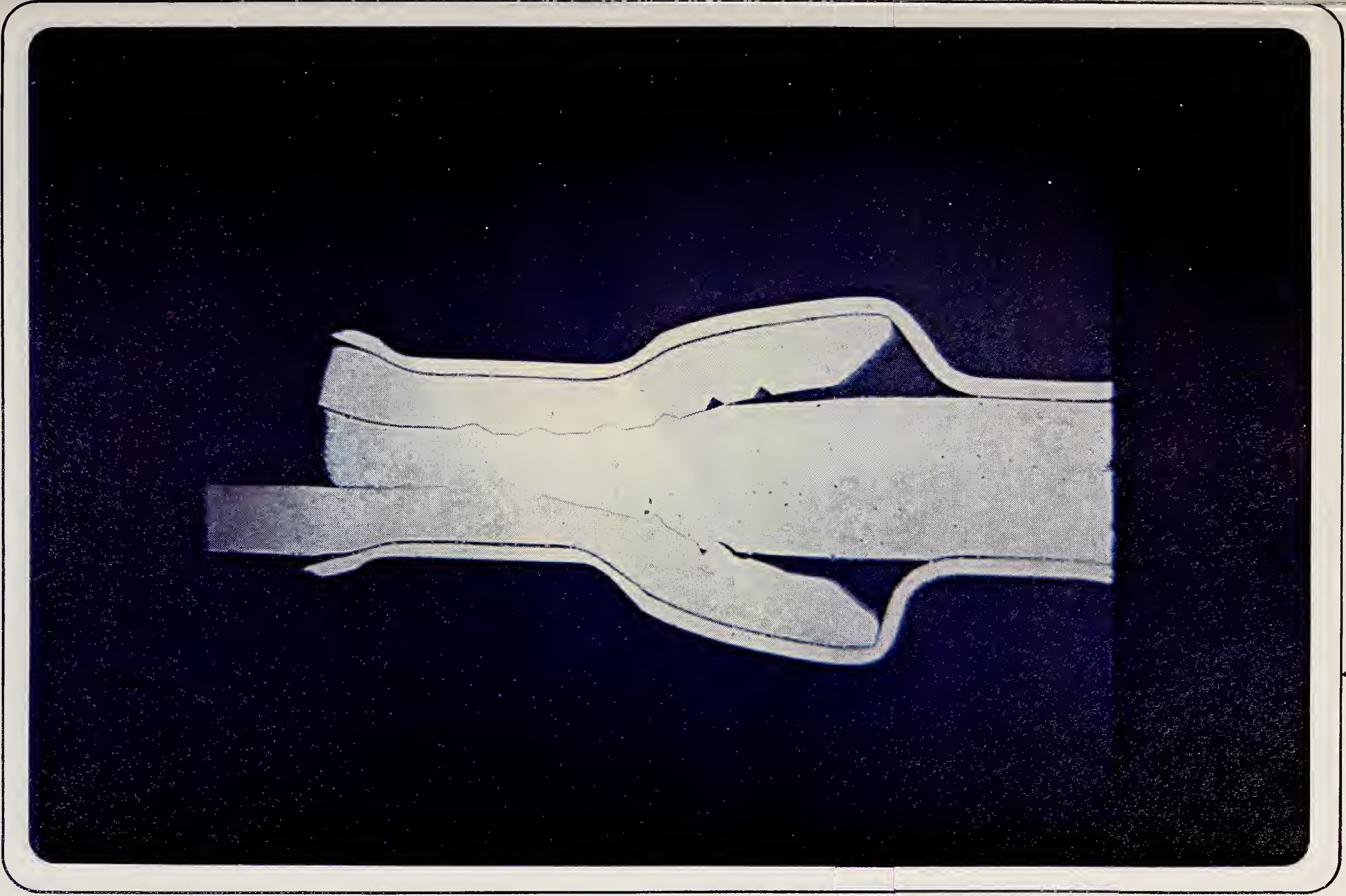

Fig. 5 Cross section of Terminal A through the longitudinal axis of the wire.

Fig. 6 Cross section through the crimp of splice E with a #10 aluminum and a #12 copper wire.

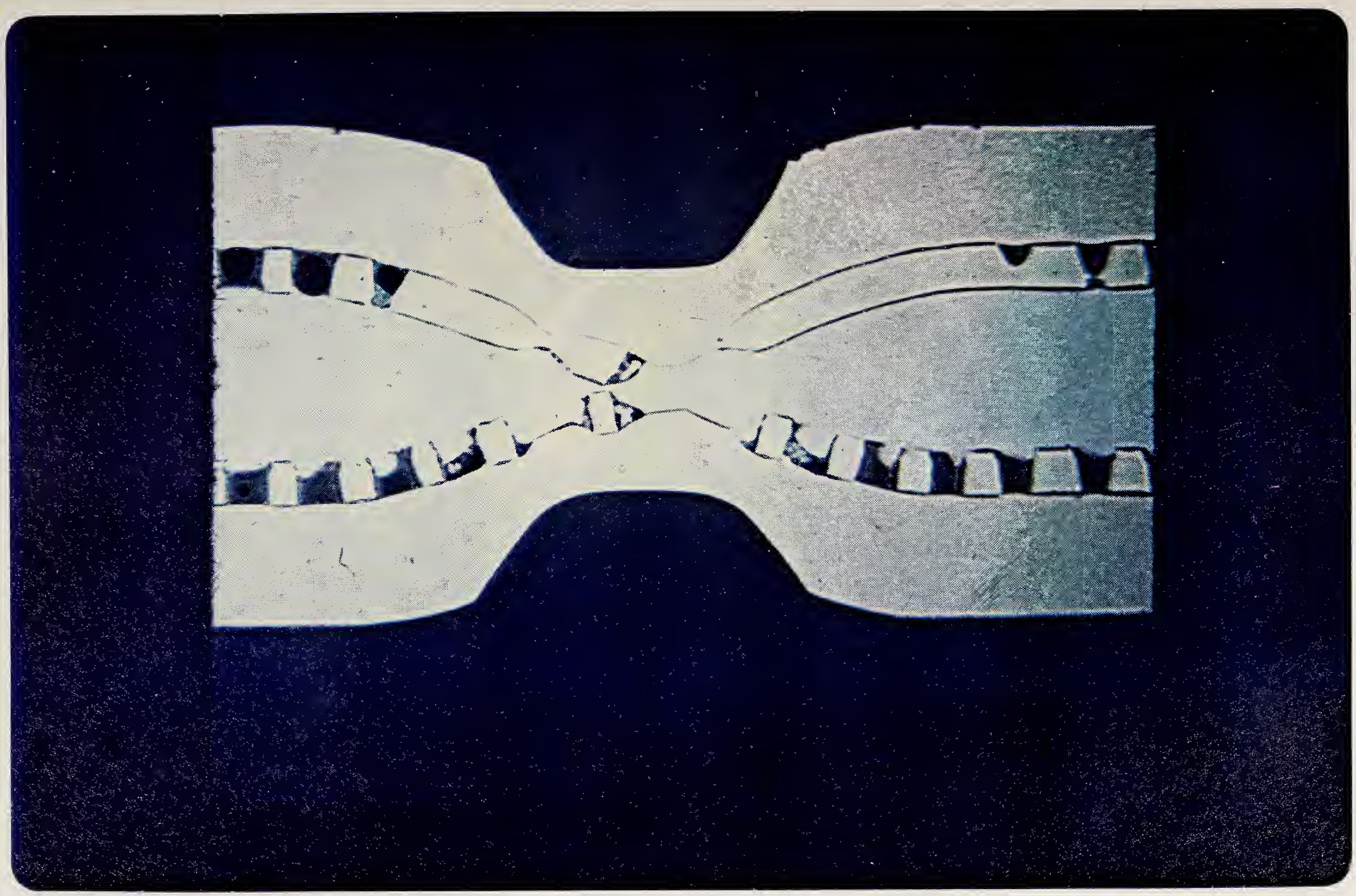

Fig. 7 Cross section of splice E through the longitudinal axis of the aluminum wire.

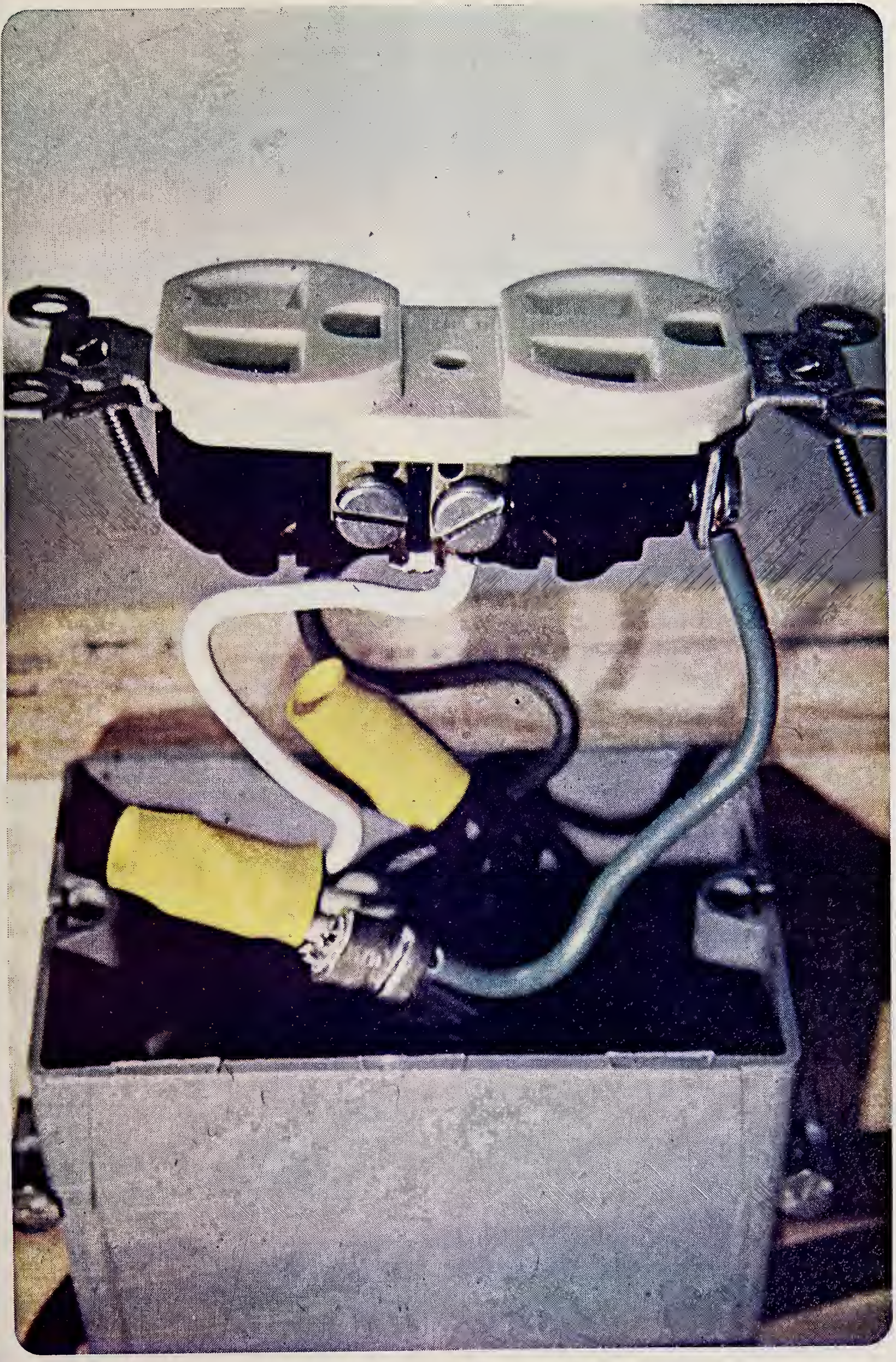

Fig. 8 Application of splice D with two #12 aluminum and one #14 copper wire all entering one end of the splice

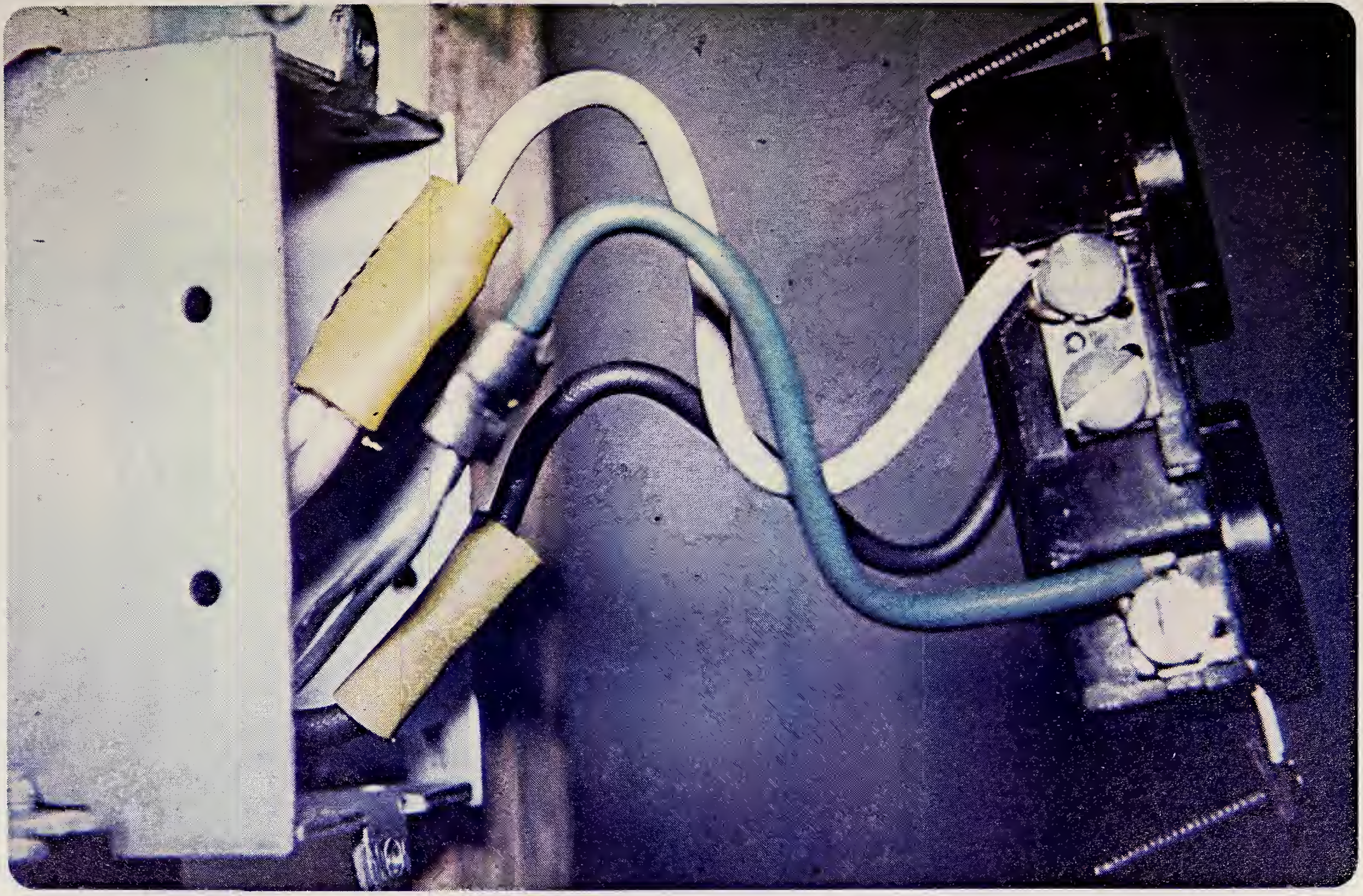

Fig. 9 Application of splice D with two #12 aluminum wires entering one end and one #14 copper wire entering the other end.

Fig. 10 Crimping tool used on splice D.

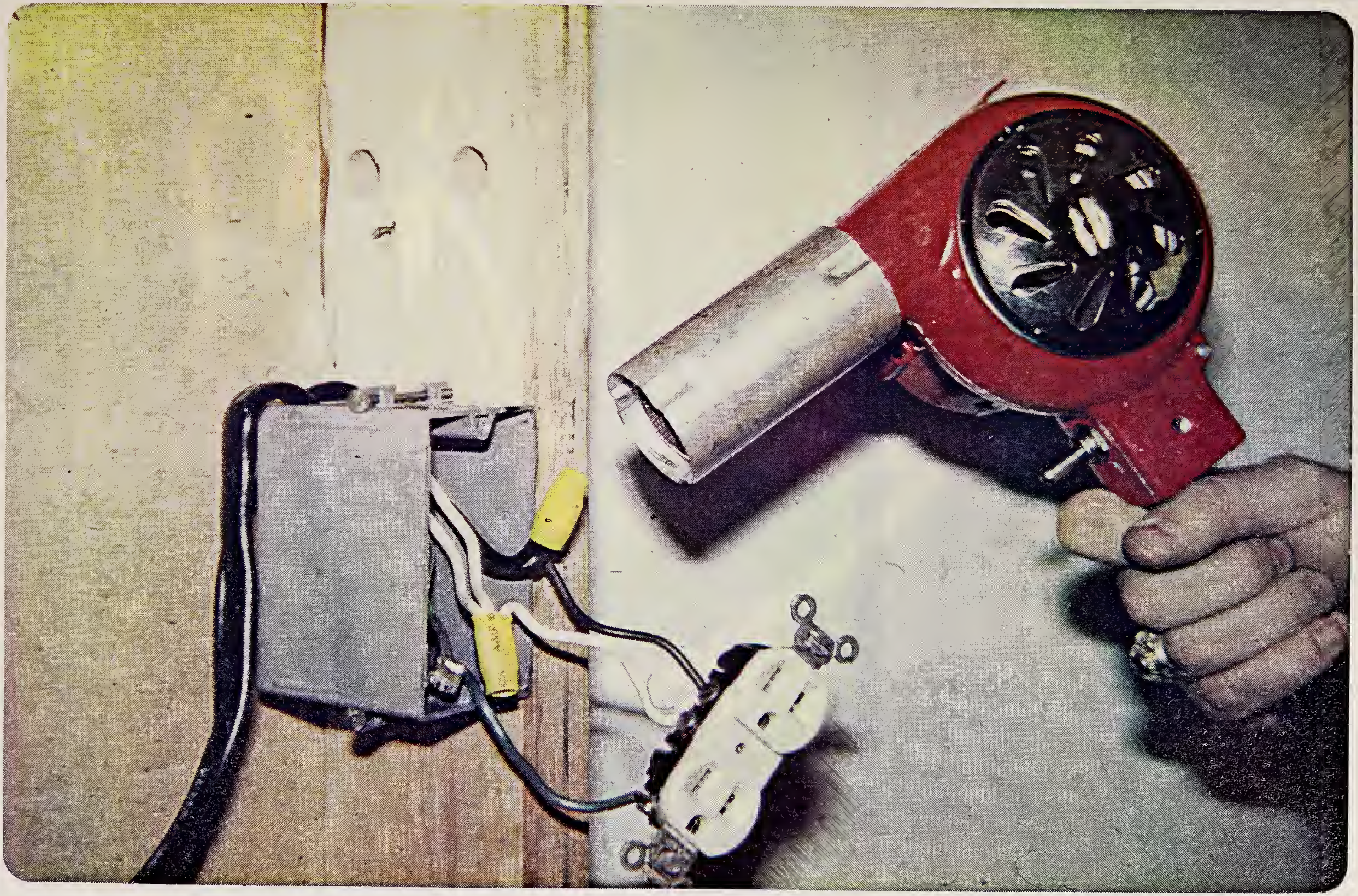

Fig. 11 Heat gun is used to shrink insulation sleeve over splice

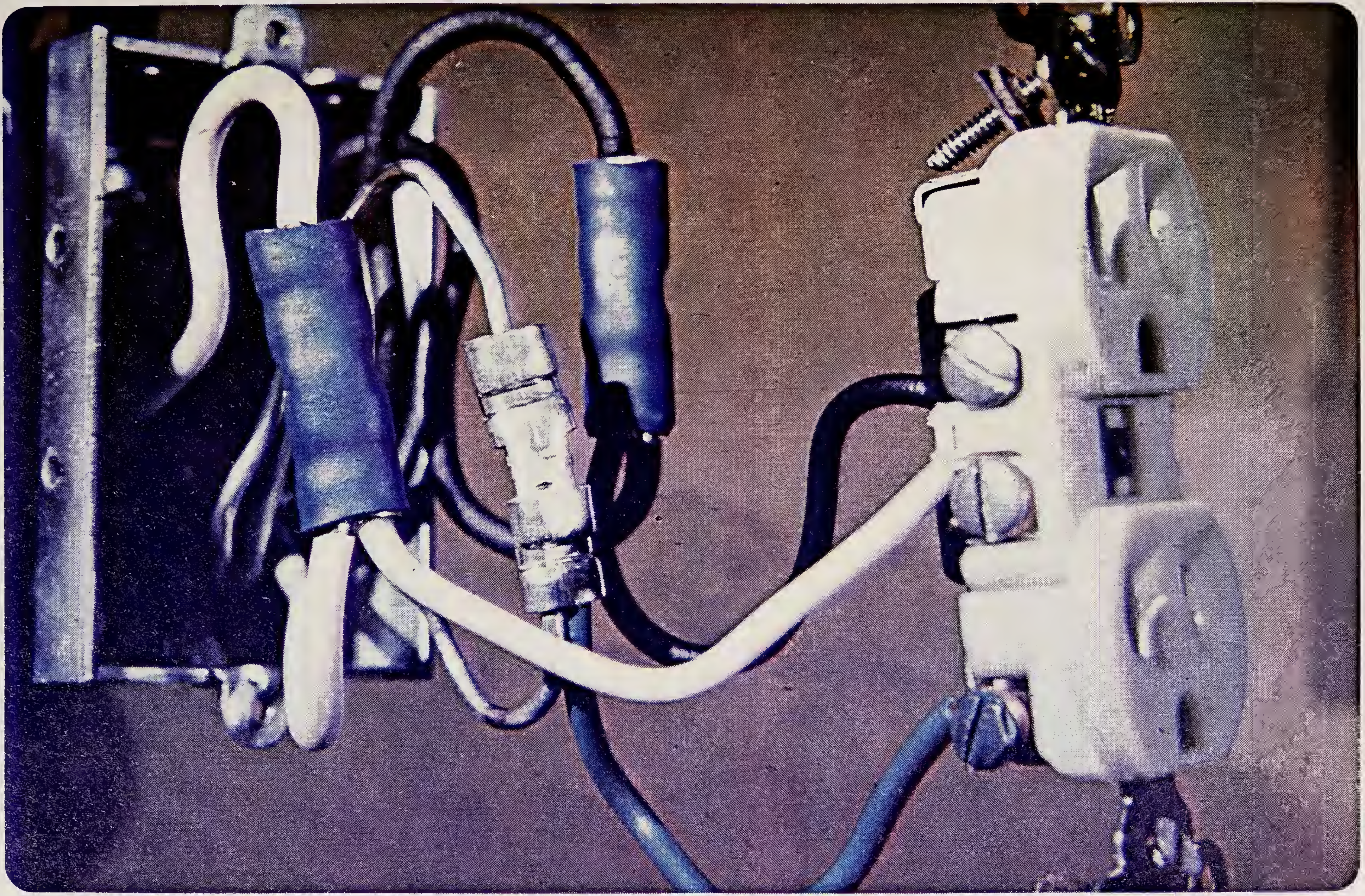

Fig. 12 Application of butt splice E with two #10 aluminum wires and one #12 copper wire

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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.)*

Systems of connecting aluminum wire for possible use in receptacle outlets and elsewhere in 15 and 20 ampere branch circuits in residences are available as practical alternatives to the presently used mechanisms such as the wire binding screw and the twist-on "wire nut" connector. The alternative systems are based on the principle of high deformation of the wire in the connection to achieve more permanent metal-to-metal fittings and/or wire splice devices of several designs. They involve either crimping the device around the wire or swaging the wire into the device with special tools. Based on tests, basic connection performance of several high-deformation connectors has been established. The results indicate that certain designs of connectors operate with stability and without dangerously over-heating under accelerated laboratory tests. The tools, however, to be used to crimp terminals are not only bulky and awkward to use but quite expensive. Moreover, they must be correctly coordinated with the terminals and sizes of wires used. There is danger that a misadjusted or improper tool and/or terminal may be used with particular wire or wires which could result in a poor connection. Some improvements in the design of the assembly tools and in the devices themselves would reduce certain installation difficulties encountered during testing, and certain connectors could be slightly modified to avoid human errors during assembly. Use of these systems and conformance with established codes and standards do not appear to present major problems.

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 wire; splices; terminals

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