NBSIR 75-723

Aluminum Branch Circuit Wiring in Residences Summary Report for the Consumer Product Safety Commission January-September 1974

By the Staff of the Institute for Applied Technology

Office of Consumer Product Safety
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

June 1975

Summary Report

Prepared for
U. S. Consumer Product Safety Commission
Washington, D. C. 20207

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U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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FOREWORD

During the late 1960's, a considerable number of reports of problems with residential aluminum wiring began to appear. These reports dealt with overheated outlets, flickering lights, and more serious events. Several surveys were undertaken to assess the situation. Soon afterward, intensive experimental work and testing began at laboratories such as the Underwriters' Laboratories and Battelle Institute. Better aluminum alloys were developed by wire manufacturers and improved components for house wiring such as CO/ALR receptacles and switches were developed by device manufacturers. UL standards on aluminum wire and related devices used in electrical branch wiring were considerably strengthened.

When the Consumer Product Safety Commission came into existence in 1973, the aluminum wiring problem came under its jurisdiction. This problem had two main parts:

(a) What was to be done about the estimated 1.5 to 2 million homes with "old style" receptacles and the older types of aluminum wire?

(b) Did the new devices and the new aluminum alloys make for a completely safe system?

During 1974, the National Bureau of Standards, as technical advisors to the Commission, did considerable laboratory work on this subject. This involved many activities including cyclic testing of connections, studies of resistance in screw connections, metallurgical studies of the interface between aluminum wire and screw connection, the effect of screw torque, etc. Old and new style receptacles were used as well as a variety of pressure connectors such as wire nuts and crimp lugs.

In the late summer of 1974, the Consumer Product Safety Commission requested NBS to prepare a special report summarizing its work up to that time as well as the work of other laboratories with a major effort on aluminum branch wiring. As part of this special report, the NBS staff was also requested to abstract the voluminous testimony that was gathered at public hearings held by the Commission in March and April of 1974.

This report has been prepared in compliance with these requests. Although many persons were involved directly and indirectly in its preparation, the report is principally the work of the following NBS staff members.

Jacob Rabinow	Chief Research Engineer Institute for Applied Technology
John R. Sorrells	Consumer Product Specialist Product Engineering Division
Larry W. Masters	Research Chemist Structures Materials and Safety Division
Robert O. Stone	Section Chief Product Engineering Division
Laurence M. Andrews	Physicist Office of Consumer Product Safety
Sidney Greenwald	Electrical Engineer Office of Consumer Product Safety

ABSTRACT

This report is a compendium of information on aluminum wiring in residences, originally prepared for the Consumer Product Safety Commission. It contains a summary of experimental research carried on at the NBS laboratories on the problems of terminating aluminum wires to screw connections as well as other pressure connectors. Since this report is an overview of the technical aspects of the aluminum wiring problem, it also contains a review by NBS staff members of available material furnished by Underwriters' Laboratories and Battelle Institute. Both of these institutions are major contributors to this particular field of information.

The report also includes abstracts by NBS staff of some four volumes of testimony taken at public hearings at Washington, D.C. and Los Angeles, California during the spring of 1974. Additional information on the pertinent physical properties of aluminum, information on failure mechanisms, possible corrective actions, connector cycling tests, etc., is given in a brief literature survey and two relevant memoranda on the subject. The report concludes with a fairly extensive bibliography.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

September 3, 1974

MEMORANDUM FOR: Mr. Richard Armstrong
Consumer Product Safety Commission

From: Jacob Rabinow, Director
Programmatic Center for Consumer Product Safety

Subject: Aluminum Wire

We are transmitting herewith the following:

A. Summaries of work on aluminum branch wiring at (1) Underwriters' Laboratories, (2) Battelle, and (3) NBS.

B. Summaries of some literature on the subject.

C. A digest of various testimonies presented to the Commission at the Hearings held in Washington and Los Angeles.

The following will be an attempt to discuss the nature of the connection between aluminum wire and various terminations and our best technical understanding of the mechanism of the connection and the mechanism of failures when they occur.

Aluminum has four properties that raise problems in electrical connections. It has a rather high coefficient of thermal expansion; it exhibits a relatively high amount of creep or stress relaxation as compared to steel or copper alloys; it oxidizes readily and the oxide is hard and brittle; and it has a higher electrical resistance than copper and, therefore, has to be used in thicker sections for equivalent current. Moreover, aluminum oxide is an excellent insulator. Therefore, to make a connection to aluminum wire, the oxide must be broken through and the connection made to the metal itself.

It is estimated that close to two million homes have been wired with aluminum wire to date and a great deal of trouble has been experienced, particularly with old wires and old connectors. The wire that was commonly used before approximately 1972 was particularly poor. It showed high stress relaxation and was physically difficult to work with. Also, the devices to which such wire was connected were not designed for aluminum wire. During the late 1960's, steel screws were introduced and are still found in many non-CO/ALR devices.

In the last two years, a new series of devices became listed by UL for aluminum wiring. These CO/ALR devices with the new alloy wires have given relatively little trouble, and neither laboratory tests nor reports from the field indicate any particular amount of difficulty.

UL has been testing a large number of CO/ALR devices for approximately two years and has had no failures. We tested two of the devices at NBS and the report on these two devices, by Mr. Sorrells, is attached.

We have reports that the CO/ALR devices with the new wires actually behave better in laboratory tests than copper wire with push-in terminals when subjected to the same tests. This implies that the CO/ALR device with aluminum wire is actually better than the widely used copper connections. We believe that the reasoning behind these arguments cannot be supported by any kind of logic and that such comparisons are meaningless.

At this point it would be well to review the present methods of testing the behavior of aluminum wiring and the devices to which it is connected. The wire is connected to conventional screw terminals with screw torques lower than those which would be applied by careful workers. The most commonly used torque is six inch-pounds. In order to accelerate the test, the terminals are then subjected to rapid heating and cooling by the passage of large currents through the connections. Values of 40 amperes and 53 amperes are quite common. These currents are passed through connections designed for normal operation at 15 or 20 amperes.

It should be recognized that the value of the current has no significance except that it produces high localized heating at the screw terminals. Battelle feels that the value of the current should not be pre-set but rather that the temperature to which the terminal is raised is important and the current should be adjusted to give the desired temperature rise at the terminal. We at NBS are making some tests where the connections are heated with blasts of hot air with no current passing through the terminals at all. All three methods of testing produce similar results in that some terminals can be made to fail by any of the means.

When the same heavy current test is applied to push-in copper connections, failures occur frequently - a failure being defined as overheating. This is to be expected since these terminals have very small areas of contact and do not provide a heat sink that is at all comparable to that of aluminum screw terminations; hence, they are more sensitive to overload currents. We have seen no evidence that supports any conclusion that CO/ALR-aluminum connections are better than the push-in copper connections at the rated 15 or 20 amp current.

The same type of logic applies to the testing of wire nuts with heavy current. These devices have a very small amount of material in contact and the joint is surrounded by an insulating jacket so that the ability to dissipate heat is very low. Therefore, testing wire nuts with very heavy currents is, again, meaningless. We believe they should be tested at currents for which they are rated. While on the subject of wire nuts, it is our opinion that they appear to be satisfactory for connecting solid wires to solid wires but they are unsuitable to connect stranded copper wires to solid aluminum conductors, particularly for large currents such as obtained in heating systems, ovens, washing and drying machines, etc. We believe that for such connections, pigtailing should be used with solid copper wires connected to solid aluminum conductors and that pressure screw type connections should be used, if at all possible.

When aluminum wire is put under a binding head screw, the mechanism of the connection appears to be the following: The wire is pressed against the plate of the connector, the oxide is cracked, and the higher the pressure the lower the resistance because, apparently, more metal comes into contact with the plate. The resistance of the connection exhibits a large dependence on pressure, as one would expect. The variation is smaller when the plate is coated with indium because the indium apparently easily penetrates the cracks in the oxide and makes connection to the aluminum. It has also been noted that copper wire exhibits a smaller variation of resistance with pressure because its oxide is very much more conducting than aluminum oxide and the mechanism of contact is, therefore, different.

The screw head makes contact with aluminum wire in a slightly different manner. As the screw turns, it abrades the wire and the electrical resistance between the wire and the screw is generally much lower than the resistance between the wire and the plate. In some cases, 3/4 to 5/6 of the current flows between the wire and the screw with the rest flowing between the wire and the plate. The current then has to pass from the screw to the plate through the threaded connection. Contact resistance between wire and screw head is much less dependent on pressure.

It is obvious, from consideration of the geometry of this type of connection, that it is very difficult to predict the behavior of the joint. For a connection to be made effective, there must be pressure between the aluminum wire and the rest of the structure. It is obvious that if the structure were perfectly rigid (that is, if it had no elasticity) a small amount of creep of the wire would reduce the contact force to zero and effective metal-to-metal contact would be lost. Fortunately, the structure does have elasticity in the shank of the screw, the head of the screw acts as a spring washer and the plate itself acts like a spring when deformed by the tension of the screw. The shape of the wire loop is far from a precise structure and there are considerable tolerances in the parts of the connector. When to this are added the fact that the plate thickness and the plate material have considerable variations along with the tolerances in the screw, we would expect considerable variation in the final force and springiness of the whole connector mechanism. Moreover, the finish of the threads and of the lower surface of the screw head and amount of lubricant, if any, are not carefully controlled. This means that a specific torque on the screw does not produce a predictable compressive force on the wire. The net result of these variations is that, in testing large numbers of connections under standardized current or temperature values, it is not possible to predict with accuracy which connections will fail or how long they will last.

There have been many theories advanced as to the exact mechanism of the failure. One theory states that motion of the wire in the connection causes corrosion to build up, thereby increasing the electrical resistance. This raises the temperature which leads to more corrosion and, ultimately, to failure. Another theory suggests that when the current is passed through the joint, the aluminum tends to expand more than the other metal parts of the connection. The wire then extrudes laterally and when the connection cools again the wire is loose and the connection is on the way to failure. There are also theories of electro-chemical action, particularly with zinc plated steel screws. There are also the effects of vibration and corrosion caused by external influences.

Finally, there is a theory which seems to us to be the more rational. It has to do with the relaxation of stress in the wire. If one assumes that a piece of aluminum is compressed under a screw and one thinks of the long-term constant temperature picture, it is obvious that as the stress in the wire relaxes, force on the wire is reduced, the effect slows down and the stress will never go down to zero. Assume, however, a more practical case. The connection is cold for part of the time, as during the winter months. The stress is slowly relaxing and is now, at the end of winter, at some fraction of its original value. If now the circuit is loaded by a device such as an air conditioner and the ambient temperature rises at the same time, a new condition of stress is set up and the wire begins to relax at a new and higher rate. If this condition continues for the rest of time, again the stress would take an infinite time to go to zero. But, if at the end of summer, the electrical load is removed and the ambient temperature again drops, the condition of the connection may be such that the force on the wire may, in fact, be zero and the wire may be completely loose. Now the oxidation can proceed full force and the connection can fail. If one adds to this scenario the possibility that the aluminum may expand more than the other components of the connection so that the wire was stressed heavily during the rise in temperature, the condition necessary to failure on cooling can be readily obtained. This is, undoubtedly, one of the reasons why accelerated heating and cooling does produce failures and why a well-designed connector for aluminum wire (or, for that matter, for any wire) should be made with sufficient "springiness" to keep the connection tight under any foreseeable conditions and for any desired length of time. We have some doubt that any of the simple devices used for branch wiring today really meet these requirements, but this is only an opinion and is not substantiated as yet by hard evidence.

In experiments with steel screws, it has been observed in our laboratories that it is possible to obtain red-hot connections either with aluminum or copper wire under the following conditions: The connection is made quite loose, a current of some 10 to 15 amperes is passed through the joint, and the wire is disturbed. An incandescent spot at the junction of wire and screw is easily observed and the spot persists for as long as the current is maintained. In fact, the current can be shut off and restarted and the incandescent spot reappears. It was found that a small weld is produced between the wire and the steel screw and the resistance of this weld is high enough to cause the metal at the joint to become incandescent. The heat eventually spreads and the whole connection becomes extremely hot. A fire can be easily started by touching the metal with a piece of paper or other flammable material.

This type of small spot weld can be produced between different types of wire and brass screws, also, but the weld does not become red-hot under normal current. The explanation is that steel is ten times poorer as a conductor of electricity than brass and has a thermal conductivity one half as great. Therefore, the temperature rise of a welded joint between the wire and a steel screw would obviously lead to much higher temperatures than if a brass screw were used. It is fortunate that all CO/ALR devices use brass screws and do not lead to the initiation of fires in this manner.

All tests so far at Battelle, UL, and NBS indicate that indium plating has a beneficial effect upon the quality of electrical connections made with aluminum wire. There is some concern caused by the fact that indium slowly interdiffuses with brass and forms a hard alloy. According to a Bell Laboratories' report, this would take several years at normal temperature but would happen very rapidly at elevated temperature. Preliminary reports indicate that when interdiffused indium was used in CO/ALR devices, the connections were still quite satisfactory. We do not have any explanation for this and the tests are continuing. Bell Laboratories, who developed this technique, recommend that nickel plating be used under the indium to eliminate the interdiffusion. So far as we know, no CO/ALR devices use nickel plating today.

In reviewing the work of NBS on aluminum wire, it should be noted that most of our work was done with non-CO/ALR devices. This was done deliberately to obtain failures in the minimum time since it was recognized that CO/ALR devices with new wire fail so infrequently and take such a long time for testing that there would be no point in repeating the work of UL and Battelle. There is some question in our minds, of course, as to whether tests on non-CO/ALR devices with new wire or CO/ALR devices with old wire would have significant bearings on "new technology" connections. There seems to be a consensus, however, that the new combination would be far better than the old. It is important to determine whether the old wire would behave well when connected to the CO/ALR devices. The answer appears to be in the affirmative and we have very little doubt that in those cases where a house is wired with old type wire the replacement of old devices with CO/ALR devices would lead to a safer installation.

Many comments have been made in various testimonies and in various reports that many of the aluminum wiring problems were due to poor workmanship. With this there can be no disagreement but it is difficult to assign the proper weight to the importance of the argument. If one assumes that with education and various forms of social pressure the workmanship can be kept at a high level, then the dependency on good workmanship is, of course, very important. If one assumes that workmanship over the long term would be no better than it has been in the past, then every effort should be made to design electrical connectors and all other related equipment so as to be satisfactory even when poorly installed.

In our many discussions with representatives of industry, UL and Battelle, there has never been any disagreement with the proposition that better connectors for aluminum wire can be designed. In this connection, it should be pointed out that much of the airplane wiring today is made with aluminum and even though the wires are usually stranded, good connections to the wire are made by terminal lugs specially designed for this service and by the use of special tools. We have seen demonstrations of such terminals and there is little doubt that excellent aluminum connections can be so made but at a considerably higher cost. The use of lug terminations would, in most cases, require changes in the design of the terminals to which they are connected. CO/ALR devices, for example, would give rise to difficulty when lugs are used because the wire restraints would interfere with the lugs. Some of the old devices would present no such problems but would have other problems. The lugs also take up some space and, unless properly insulated, may cause trouble by shorting to the boxes in which the devices are mounted.

We have experimented with some new types of connections where the screw is not part of the circuit and one particular type seems to be promising. Basically, the wire is used in a conventional way except that it is held between two surfaces of the plate itself and its screw is not part of the electrical circuit. This enables us to use one or more Belleville washers to provide "spring" in the connection and to maintain the pressure on the wire when the wire expands, contracts or creeps. Almost any amount of "follow up" action can be provided by this means. The surfaces of the plate contacting the wire should have a series of sharp projections like those which one finds on a rasp. Such projections are also found, for example, on a Thomas and Betts' washer designed for aluminum connections.

We also feel that some indication of tightness of screws should be built into the connector so that inspection, at the time of wiring or at some later date, would reveal whether the connection was properly made. We have experimented with twist-off heads on screws and plastic attachments to screws to indicate the maximum torque applied to the screw. In such designs, the upper head of the screw or a plastic attachment to the regular head is stripped off when the correct torque is applied. A Belleville washer can also act as an indicator of maximum force. When the Belleville washer is completely flattened, the correct torque is obtained. There is a distinct change of "feel" when a Belleville washer is used and the reaction on the screw driver suddenly becomes greater when the washer is flat.

We are certain that many other types of connectors can be designed for aluminum and copper wires which would be just as easy to use as at present, which would cost only slightly more, if at all, and which would lead to more positive results than any of the present connections that we have examined in outlets, switches and wire connections.

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

Date: August 30, 1974

To: J. Rabinow
Director, Programmatic Center for
Consumer Product Safety

From: John R. Sorrells
Measurement Engineering Division

Subject: Measurements of CO/ALR Receptacles from UL Laboratories

In accordance with your request, resistance and torque measurements have been made on two CO/ALR receptacles which were removed from UL's test rack during your visit to the UL Laboratory on August 21, 1974. Receptacle No. 1 had been subjected to 4292 test cycles and receptacle No. 2 had been subjected to 5091 test cycles at the time of their removal. In each test cycle the receptacles were subjected to a 53 ampere test current which was on for 3-1/2 hours and off for 1/2 hour. Both receptacles were wired with #10 AWG aluminum wire of a type that is not approved by UL. Initial screw torques at the start of the test was 6 inch-pounds.

To test the condition of these devices after extended cycling, voltage drop measurements were made on all eight connections, using the same technique which we use in our other tests. From these measurements, the various interface resistances and the net effective resistance for each connection were calculated. After the above measurements were completed, residual torque measurements were made on two of the eight screws. For these measurements, the connection on each receptacle which had the highest effective resistance was selected.

On both receptacles, the various interface resistance and the effective connection resistances were found to be consistently low. On receptacle No. 1, the average effective resistance of all four connections was only .00004 ohms higher than that of newly made connections, made in an equivalent manner on the same manufacturer's device. On receptacle No. 2, the average resistance of four connections was only .00002 ohms higher than that of equivalent new connections on the same type receptacle. In both cases, the slight increase in average connection resistance appears to be due to corresponding increases in the wire-to-plate resistance and the wire-to-screw resistance. Compared to new connections, these resistances increased, on the average, by .00023 and .00006 ohms respectively.

The residual screw torques measured on terminal II of each receptacle were 5.2 inch pounds for receptacle No. 1, and 12 inch pounds for receptacle No. 2. I have no explanation for the apparent increase in torque on receptacle No. 2 except that in making the measurement, I noticed that the connection felt very "hard" as the clockwise torque was increased, almost as though the screw was rigidly bonded in position. At 12 inch pounds it rotated quite suddenly as if the "bond" had been broken.

SUMMARY OF ALUMINUM WIRING HEARINGS

The following are abstracts of the testimony developed at public hearings on aluminum wiring before representatives of the Consumer Product Safety Commission. These hearings took place on March 27-28 in Washington, D.C., and on April 17-18 in Los Angeles, California. It includes testimony of individuals from research and testing laboratories, wire and device manufacturers, trade associations, electrical contracting firms, electrical inspection and fire departments, and consumer organizations. It does not include the testimony of "interested" individuals" which is abstracted elsewhere by the Consumer Product Safety Commission staff.

1. WILLIAM ABBOTT - BATTELLE INSTITUTE - LOS ANGELES TESTIMONY

Abbott believes experience with heavy aluminum wire cannot be extrapolated to branch wiring. Asserts that a presently stable connection can fail in one minute or one year, and no measurement can predict this. Poor workmanship a factor but should not be overemphasized. Early failure usually caused by loose screws with copper or aluminum. Failure with tight connection is statistical and depends on material, device design, and operating conditions. He believes failures can be predicted statistically out to 50-100 years. All failures, however, are not hazardous.

Two aspects of termination are: (1) initial good contact, and (2) maintenance of good contact. To break or wipe oxide off wire takes only 3/4 to 1 1/4 in.lbs. for copper and 1 to 1 1/2 in.lbs. for aluminum, but this will not keep connection good.

Copper and aluminum alloys (since 5/71) lose about a maximum of 25 to 30% of their force under a screw in 5-10 years at room temperature. EC aluminum in range H16-H19 loses 60 to 70% in 2 to 3 years. However, he finds no correlation between stress relaxation and performance. He says failure mechanism is due to small motion between wire and plate and wire and screw during thermal cycling. The wear process or fretting produces an accumulation of oxide film. Challenge is to prevent micro-motion or use sufficient force and materials. Copper can take 5 to 10 times greater number of wipes than aluminum. Aluminum needs higher force to stop motion or overcome its effects. With no motion there should be no failure. With motion, bare aluminum fails first, then nickel coated aluminum, and then copper or copper-clad aluminum.

Worst case conditions for connection involve high cycling rate, high temperature, and low torque. The old aluminum wire, environmental stresses, and installation practice add to problem. Technology exists for a lifetime of hundreds of years, but he doesn't know if that has been achieved with CO/ALR devices.

Push wire system not reliable with aluminum. Of the 3 wire nut combinations tested, aluminum-aluminum, aluminum-copper, and aluminum-copper-aluminum, the Al-Cu is most reliable and the Al-Al the lowest level of reliability. Abbott considers the quality of an Al-Al connection intermediate between a binding screw and push wire connection. Neither of the two approved UL devices that were tested will take 40 amps, but there is not yet enough data on the subject.

With the old steel screw receptacles with copper rated as 1, nickel-clad wires are 6-32 times more likely to fail, 400-1000 for UL alloys, and 1600 to 3000 for other wire types.

Abbott would not give a figure on how long a CO/ALR device would last with the old wire. He feels CO/ALR devices are better, but doesn't know how much. He also would not put a figure on time to failure for copper wire. The UL test should be done on a temperature basis instead of current. He makes a distinction between failures and fires, and stresses the importance of linking laboratory work and field statistics.

2. DAVID CONDRA - SOUTHWIRE COMPANY - LOS ANGELES TESTIMONY

He feels that the copper shortage in 1966-67 which caused device manufacturers to change from brass to steel screws had an enormous effect on consequent problems. Triple E wire was introduced in 1968 not as an answer to failures but to improve the handling characteristics of the wire. Main property of aluminum pertinent to making connections is oxide film. This forms almost instantaneously and is .0000001 millimeters thick.

It is a very thin, brittle substance which is easily fractured. Therefore, good initial contact to aluminum presents no problem.

Problem occurs under heat cycling when a loose connection permits the oxide to reform under the conditions of expansion and contraction. A steel screw with half the rate of expansion as aluminum leads to stress relaxation, more oxidation, higher temperatures, and the destructive cycle regenerates.

Mr. Condra went through the UL cycle test explaining how it stressed the operating conditions of wire and device. He believes that the destructive effects in screw connections can be prevented by:

1. Better initial contact by more tightening, low resistance screw material, softer wire, improved wire surface characteristics.

2. Better heat dissipation to keep temperature low.

3. Making screw of material with an expansion coefficient similar to the wire, so that different expansion properties cannot cause problems.

According to Mr. Condra, failure requires the simultaneous occurrence of worst cases, i.e., poor quality of wire, steel screws, low thermal mass, poor installation and inspection, and high circuit loading.

Tests at Southwire and elsewhere show that the new aluminum alloys with CO/ALR devices provide a more reliable system than does copper with push-in or back-wired devices.

Based on his belief in the effectiveness of local action, he made three suggestions to the CPSC:

1. If Commission believes in the reliability of aluminum wire-CO/ALR system, this fact be widely disseminated.

2. In localities where problems exist, CPSC act as a force to initiate convening of local groups for solution of such problems.

3. He recommends continued research by all interested parties including NBS.

3. ELECTRICAL CONTRACTORS - WASHINGTON AND LOS ANGELES TESTIMONY

Four contractors testified at these hearings. Two - Reece and Williams - were invited by the Aluminum Association or Southwire because of their satisfactory experience with aluminum. The other two - Nickrehm and Rubin - contributed very little to the hearings since they do not use aluminum for 15 and 20 amp. circuits. The testimony of Reece and Williams indicated primarily that with good workmanship aluminum is satisfactory, even with the old aluminum wire and old fixtures.

Reece (II-532) started using aluminum in 1964 and now uses over a million feet a year. He claims to have no more problems with aluminum than with copper and believes that 90 percent of the aluminum problem is due to poor workmanship. He uses a journeyman electrician on every job. All other workmen are apprentices. Has an incentive for good workmanship by giving a bonus for each completed job which does not require a service call during the 12 month warranty period.

Williams (II-551) started using aluminum in 1966, and is now using aluminum for about 98 percent of their work. His company has over 100 employees, and he claims they have not had a failure using aluminum branch circuits. They emphasize training, incentive, and workmanship. Also select their material - do not use "quick-wired" fixtures. The company has a profit sharing plan which is an incentive to good work.

Knickrehm (IV-378) does commercial wiring. Does not use aluminum for 15 and 20 amp circuits because the code in their area does not allow it.

Rubin (IV-436) uses copper for 12 and 20 amp branch circuits and aluminum for heavier duty circuits. This choice was not due to safety considerations but due to fact some counties in their area do not allow aluminum branch circuits. The company, therefore, does not stock both aluminum and copper in the smaller sizes.

4. LOCAL OFFICIALS - WASHINGTON AND LOS ANGELES TESTIMONY

Local officials who are concerned with fire safety should be among the most objective witnesses regarding aluminum wiring. In general, their testimony was that the risk of electrical failures and fires was much higher for aluminum wiring than for copper. It should be noted that this was for the older wire and fixtures.

Usually the officials were not involved in determining the detailed cause of failure. However, since the failure rate varied from one locality to another - and they were using essentially the same wiring and materials - it can be inferred that the main variable was workmanship and, hence, this was a factor in the failures.

Kelley, Electrical Inspector, District of Columbia Fire Department (I-21). The data presented by Kelley were for large electrical fires - service equipment and feeders. He felt that their problems, however, were related to the residential problems in that all their failures have been at the terminals or junctions. Has had more "large" fires with aluminum than copper, but data do not indicate relative usage of the two materials. Suggests possibility of preventative maintenance - checking terminals annually - which may be practical for large equipment but not in a residence.

Kuntz, Chief Electrical Inspector for Prince George County, Maryland (I-93). Out of approximately 45,000 dwelling units wired with aluminum there have been about 100 failures resulting in structural damage. Poor workmanship was noticed on many of these failures. In March 1972 the county banned the use of aluminum wire in sizes No. 6 and smaller; hence, they have no data on the CO/ALR devices.

Termination failures have occurred from eight days to eight years after first occupancy. This is in contrast to the opinion of some other witnesses that failures will manifest themselves within a few months.

Kuntz believes that a certain amount of poor workmanship is inherent in the construction industry and that any solution to the aluminum wiring problem should not be dependent upon better workmanship than we have had in the past.

Flach, Chief Electrical Inspector of New Orleans (I-220). Aluminum wiring has not been a serious problem in New Orleans. They have had a few problems with loose terminals, but he feels the problem is manageable through good inspection and education of the contractors.

Duncan, Huntington Beach Fire Department, with Mr. Dart, Chief Electrical Inspector (III-6). Their community had a marked increase in residential electrical failures in 1970. They surveyed the neighborhoods which had these problems and found that there were far more problems than had been reported. Due to this, as well as the death of a resident due to an electrical fire, the city passed an ordinance restricting the use of bare aluminum in branch circuits.

They are still having problems with this aluminum wire - about 80 fire incidents since mid-1970 due to aluminum wiring. For comparison, they have had only one incident attributed to copper in this period. (This again indicates that all failures do not show up in a few months. These long-term failures with the old materials are not well understood.)

Dart pointed out that electricians do not use torque screwdrivers. He had never seen one. Duncan claims that they have had failures with terminals that were quite tight. He doubts that poor workmanship is the only cause of these problems.

Huntington Beach allows the use of copper-clad aluminum. They have had no experience with CO/ALR devices since these are not required with copper or copper-clad aluminum. Dart feels strongly that the quick push-wired devices should not be used with copper-clad aluminum. Pushing the fixture back into the outlet box tends to wring off the copper and there is only an aluminum junction which leads to failures.

Duncan is also chairman of the California Statewide Fire Prevention Officers Electrical Committee. He has been active in bringing the problem of aluminum wiring to the attention of other fire departments. Has also initiated a statewide survey of electrical fires through the Fire Prevention Officers Association. He has had responses from several communities indicating that they have similar problems. In several cases they had not previously recognized that their electrical problems were due to use of aluminum.

Duncan feels that aluminum was released for residential use prematurely - the home has been used as the proving ground rather than the test lab.

Duncan also seemed skeptical of UL ratings since the old wire and terminals were also UL approved. He is doubtful that the failure mechanism has been identified, therefore, has a "wait and see" attitude on the proposed solutions.

Meyers, Mayor of Buena Park, California (III-47). Essentially confirmed the testimony of Duncan regarding the severity of the aluminum wiring problem. Also indicated that they had had problems with pigtailing splices. Buena Park has prohibited use of aluminum size No. 6 or smaller, as well as copper-clad aluminum for past two years.

Fuerstien, Fountain Valley Fire Department and President of Orange County Fire Prevention Officers' Association; and Crockatt, Tuscin City Fire Department (IV-465). Fuerstein supported the statements of Capt. Duncan and confirmed that nearly every city in Orange County had experienced some of the same problems.

Fountain Valley has not banned aluminum, but they are now using pigtailing with the straight aluminum and are using copper-clad wire. They have had no problems with either of these methods but caution that it may be too early to tell since these installations are relatively new and that the problems with the older methods often showed up four to five years later. He also objected to "...the electrical industry... asking the public to try to survive their experiments with aluminum wire."

In the past three years the fire department has had 27 trouble calls due to branch circuit wiring. Of these, 26 were aluminum wiring and one was copper. He estimates that over 80 percent of the homes are wired with copper.

Hanson, San Bernardino County Department of Weights and Measures and Consumer Affairs (III-95). His testimony was regarding aluminum wiring in mobile homes. They have had many complaints - faulty or intermittent lights, hot outlets, and burning odors - which were traced to aluminum wiring. Electricians who specialize in mobile home work feel that poor installation is mostly to blame for these problems. Some of the residents make a practice or retightening the terminals on their outlets, and this appears to solve the problem.

Dreyer, California Department of Housing and Community Development (III-124), believes that in view of copper shortage and difference in cost that aluminum should be allowed for home wiring. May require more inspection to insure compliance with good workmanship regulations, but he would not recommend banning its use. He was speaking primarily of mobile homes. He gave production and fire data for mobile homes in California for several years and indicated that aluminum wiring accounted for only about 4 percent of all fires. (This number may be low because there may be aluminum fires which are classed "undetermined cause.")

He believes it is important that the builders, electricians, and inspectors be educated regarding the proper use of aluminum so that it can continue to be used.

Miller, Electrical Supervisor; and Hebard, Electrical Inspector, Los Angeles City Schools (III-199). The Los Angeles city schools use aluminum for services and in conduit for feeder circuits, but do not use aluminum for the branch circuits. They have had problems with terminals similar to the residential problems.

Both witnesses were critical of the electrical industry as a whole but were optimistic that the problems were solvable. They would like to see more rapid progress, however.

They were critical of the aluminum wire manufacturers for not sufficiently educating the users, of the equipment manufacturer for not recognizing that aluminum was being used and not providing proper terminals and sufficient space in the box for the stiffer wire, and of the contractors for the poor workmanship.

Hebard feels that the burden of insuring good workmanship cannot be put on the inspector - they just can't inspect everything 100 percent.

Miller emphasized the importance of the terminal having sufficient compliance to allow for the differential expansion of aluminum and terminal material.

5. OTHER WITNESSES - WASHINGTON AND LOS ANGELES TESTIMONY

Hart, National Electrical Contractors Association (I-167), believes that the problems of the past have essentially been solved. States that there will always be some problems due to misuse by untrained people for any type of electrical installation. Believes that present safety record overall is very good and gives credit to the National Electrical Code. Agrees that the code does not emphasize the greater care required when installing aluminum.

Mara, The Aluminum Association (I-200). Traced the history of aluminum for electrical work and the corrective actions taken by UL to solve the early problems.

While acknowledging that there have been problems with aluminum terminations, he does not believe that the use of aluminum represents a special risk to the consumer.

They recommend that the Safety Commission consider making the National Electrical Code mandatory throughout the United States.

They believe that the new aluminum wire together with the CO/ALR devices will give safe electrical systems even with poor installation.

Phillips, National Joint Apprenticeship and Training Committee, IBEWU and National Electrical Contractors Association (III-165). Phillip estimates that NECA contractors do not do much of the residential wiring.

Specific information on aluminum wiring was first introduced in the apprentice training material in 1971. (This would indicate that the industry was either somewhat late in recognizing the aluminum wiring problem or if recognized, they did not realize that aluminum was more critically dependent than copper on good workmanship.)

Ellis, Virginia Electric Power Company (II-439). VEPCO has been using aluminum for several years. When they first started using aluminum they discovered that connecting aluminum required more care than copper and that copper connectors were not suitable for aluminum. New designs and techniques were developed which overcame the problems encountered.

Cain, Copper Development Association (II-273), had nothing to contribute regarding the safety of aluminum wiring. The main point of his testimony was that the U.S. is becoming more self-sufficient in copper - 92.2 percent in 1972. He believes that if aluminum residential wiring was banned it would have very little effect on the copper industry. (From figures NBS has obtained from the Bureau of Mines and the Department of Commerce, this conclusion is in error - that, indeed, whether or not branch wiring were required to use copper wire, would have a very great impact on the copper industry.)

Hotchkiss, Center for Concerned Engineering; and Jarman, Center for Auto Safety (I-122). Jarman was primarily concerned with the hazard of aluminum wiring in existing mobile homes. They feel that aluminum wiring in mobile homes is a greater hazard than in conventional homes for three reasons:

1. Poorer workmanship. Also, the work is usually not inspected.

2. Transportation from factory to site with vibration tends to loosen the terminals.

3. The greater use of thin plywood panelling and plastic components made the home more flammable than the conventional home with drywall construction.

They recommend that the present owners of mobile homes with aluminum wiring be located and sent notices warning them of the dangers of aluminum wiring and recommending that CO/ALR devices be substituted for older devices and that they have their outlets inspected yearly by an electrician.

Hotchkiss traced the history of aluminum problem and blamed both the aluminum wire manufacturers and UL for the use of aluminum wire in residential electrical systems without adequate testing to insure safe operation. He believes that aluminum should not be allowed in residential use until it has been proven by field tests to be as safe as copper. He is skeptical of the proposed solution to the aluminum problem - new improved wire alloys and CO/ALR devices - for two reasons:

1. Worst case testing does not go far enough in duplicating faulty workmanship. Many workmen do not tighten screws even to six inch-pounds, the test condition specified by UL. (This appears to be a valid criticism.)

2. Cycle testing has not been demonstrated to simulate long-term life testing.

He recommends a moratorium on installation of aluminum branch circuits until aluminum alloys and associated devices are developed which demonstrate greater forgiveness to faulty workmanship.

He also feels that something should be done to alleviate the hazard in existing homes wired with aluminum.

6. T. R. PRITCHETT - KAISER ALUMINUM CORPORATION - LOS ANGELES TESTIMONY

Insulated conductors, both aluminum and copper, are automatically tested during manufacture for continuity, resistivity, and insulation defects or voids. Wiring connections, on the other hand, are made without strict quality control. Kaiser continues to do research on the effect of various impurities and intentional alloying on the mechanical and electrical properties and corrosion resistance of various conductors.

The company has a creep testing laboratory for checking creep and other related phenomena. Creep and fatigue are important metallurgical phenomena affecting wire performance. Creep relates to relaxation or change in physical dimensions of a material subjected to long-term stress. Fatigue resistance is the ability of a material to resist cyclic stressing. Ductility and the rate of strain hardening determine the brittleness of the wire and its ability to make repeated bends. The influence of alloying additions and fabricating practice on these properties has led to improved aluminum wire products and eliminated former unfavorable characteristics.

Experience with "connector aid" to improve connections has shown that it is not necessary. Kaiser's experience with the aluminum wired Ravenswood development and other Kaiser buildings has been good.

The company has made extensive cycling tests on aluminum wire along the lines of the UL tests. Pritchett believes that the changes made in receptacles such as larger brass binding screw, larger contact platc, and wire restraints make connection significantly better.

As cycling tests proceeded, engineers noted that there was a tendency for poorly-made connections to loosen. Attempt was made to record this with time-lapse photography. However, well-made connections with 12-15 in.lbs. torque did not loosen.

In poorly-made connections with 4-6 in.lbs., they found no deformation under the screw. The area of contact with the screw was small, and screw threads were barely touching. They also believe basic failure mechanism is motion between wire and screw, and also expansion and contraction of the connection with change in temperature. Creep is thought to be important only at much higher temperatures.

As a result of accelerated tests, Kaiser people believe that the combination of improved conductor and new CO/ALR devices eliminates electrical termination difficulties except in rare cases of extremely poor workmanship. They are trying to improve workmanship by educational efforts, field communication, etc.

Pritchett agreed that with low torque connections aluminum will more likely cause trouble than copper. In experimental work, loose connections showed up fairly soon, and once temperature rise exceeded 10-15°C, temperature rise was exponential, leading to failure. He felt that to try to correlate an accelerated lab test with full life is very difficult and takes a great deal of statistically reliable data.

7. BARON WHITAKER - UNDERWRITERS' LABS - WASHINGTON TESTIMONY

Mr. Whitaker indicated that the NEC is the basis for electrical safety requirements, including installation of aluminum wire. UL labeled aluminum wire since 1946, but real production started in 1965-66 due to copper shortages. By 1968, field problems with aluminum were being reported. A questionnaire was sent to contractors, inspectors, manufacturers, and users, but only a 14-17% response resulted. The statistics indicated that aluminum was responsible for more electrical problems than copper, but there was little indication of fires. This survey, however, did not cover branch wiring.

Later reports from the field indicated difficulties with screw type receptacles - flickering lights, intermittent appliances, radio static, odors, smoke, and fires.

Mr. Whitaker outlined steps UL took to prod the improvement of wire, devices, and testing methods. The Ad Hoc Committee disseminated correct installation methods and safety messages. A survey of 1,100 electrical inspectors indicated an average of 40 fires per year from 1962 to 1972 attributable to aluminum termination systems. During the same period the NFPA reported an average of 660,000 residential occupancy fires per year. With regard to public safety and unreasonable risk of injury, Mr. Whitaker said that the survey relating to binding screw receptacles indicated that approximately 30 times as many cases of nuisance performance occurred as cases of reported fires. He pointed to the effect aluminum wire has had in tightening UL standards. New materials always have problems initially, and these get corrected. According to tests, aluminum wiring failures usually occur within the first few months of installation.

Copper supplies, he said are expected to be available in volume for another 30 years only.

UL ran tests on aluminum wire in 1965 at 150% overload with success. Original requirements were for 20 in.lbs. torque. The field indications were that loose connections due to poor workmanship were the principle problem. UL tests are now made at low torque, and include bending of wires and vibration. He had no opinion on who was responsible for correcting problems.

UL indicates that aluminum wire with the same physical characteristics but small changes chemically gave differing test results. The result is that UL specifies wire physically and chemically. They are satisfied that the present testing program and requirements are adequate.

Evaluation of upgraded wire nut connections are to be made in future developmental work. UL is satisfied with test on copper-clad wire and push-wire contacts. They have no opinion, pro or con, on antioxidants.

Mr. Whitaker felt that aluminum does not have the same margin of safety as copper and, therefore, workmanship is an important aspect in proper installation. He believes that if reasonable care is exercised a good installation and service life will result.

TECHNICAL SUMMARY OF ALUMINUM WIRING RESEARCH CONDUCTED BY THE MEASUREMENT ENGINEERING DIVISION (MED)

1. SCOPE OF THIS REPORT

This report summarizes the results of engineering studies conducted on the Aluminum Wiring Project by the Measurement Engineering Division between March 15, 1974, and August 15, 1974.

2. PILOT TESTS

Before starting any long-range experiments, several pilot tests were conducted in order to identify the important parameters, to develop measuring techniques, and to characterize some of the components to be studied. The results of these preliminary tests are discussed in the following sections of the report.

3. HEAT CYCLE TEST

Preliminary tests were made on two "old style" receptacles to investigate the effects of thermal stress on typical screw terminations. Connections were made on one side of the receptacles with #12 aluminum wire with screw torques of 6 inch pounds. The four connections were then subjected alternately to forced streams of hot and cool air at a rate of one cycle per minute. The average thermal excursions measured at the break-off tabs were 43° to 110°C and 43° to 95°C respectively. Periodically, the effective resistance of each connections was measured by passing a known current through the connection and measuring its voltage drop with a digital voltmeter. At the end of 9500 cycles, the effective resistance of the four connections had increased by 12%, 9%, 29%, and 13%, respectively.

On the basis of these results, a more extensive heat cycle experiment was designed and is in progress.

4. RESISTANCE CHARACTERIZATION OF OLD SYTLE AND CO/ALR RECEPTACLES

To obtain basic information about the electrical characteristics of a variety of receptacles, resistance measurements were made on seven types of CO/ALR receptacles and seven types of old style receptacles. For these tests, the devices were wired with #12 aluminum wire and the screws were torqued to 6 inch pounds. A known test current was passed through the connections and the voltage drops for each connection were measured. From these measurements, the effective resistance of each connection and the break-off tabs were calculated. From these data, the following points became apparent.

4.1 Compared to the old style receptacles, the CO/ALR receptacles provide consistently lower connection resistances.

4.2 The resistance of the break-off tab varies considerably from device to device but on most devices tested was equal to or greater than the resistance of either screw termination. This indicates that on most devices the break-off tab contributes significantly to the thermal rise of the connection assembly.

4.3 Of the devices tested, the one having the lowest break-off tab resistance was a CO/ALR receptacle with a copper contact plate and tab assembly. The two devices with the highest break-off tab resistances were an old style receptacle and a particular CO/ALR receptacle. Both of these devices had brass contact plates and smaller-than-average break-off tab cross sections.

5. TEMPERATURE EFFECTS OF BREAK-OFF TABS

Using samples of the two receptacle types which showed the highest break-off tab resistance, a test was conducted to determine the thermal effects caused by losses in the break-off tab. On the CO/ALR receptacle this was done by passing a 40 ampere test current through the complete connection (wire-to-wire) and measuring the temperature of the screws and tab after thermal equilibrium was reached. The receptacle was then modified by soldering a brass strap across the gap in the contact plate so that the break-off tab was effectively shunted. The device was then subjected to the test current, and the equilibrium temperatures were recorded again.

Since the particular old style receptacle which was tested has a break-off tab only on one side, a direct comparison was made between the equilibrium temperatures (at 40 amperes) of the two sides of the receptacle.

From the above tests it was found that on both types of receptacles tested, losses in the break-off tab contributed approximately 17°C to the total temperature rise at the screw terminations. If connection temperature is a critical factor in its performance, the above observations suggest that the design of the break-off tab is an important consideration.

6. CURRENT DISTRIBUTION TESTS

To investigate the distribution of current in a typical binding screw connection, a series of experiments were conducted wherein insulating washers were introduced between the wire loop and the contact plate, or between the wire loop and the screw. By this means it was possible to force a known test current to flow either from wire-to-screw or from wire-to-plate. From the measured voltage drops, it was then possible to calculate the effective interface resistances between wire and plate, between wire and screw, and between screw and plate. In these particular tests it was found that the path resistance from wire-to-plate was from 3 to 5 times greater than the path through the screw and that the screw, therefore, carried approximately 3/4 to 5/6 of the total connection current.

On one old style receptacle, the current path through the screw was deliberately blocked by an insulating washer, and a 40 ampere test current was passed through the connection while the connection temperature was monitored. Within 15 minutes, the connection temperature had risen to 174°C. By UL performance criteria, this connection would be considered a failure.

Although limited in scope, the above tests clearly indicated that the screw is an important current carrying element in the receptacle connection.

7. TORQUE-RESISTANCE TESTS

To further investigate the effects and relative importance of the various connection interfaces, a test technique was devised for injecting a test current through connections either through the normal mode (from wire to contact plate) or from screw to plate. From voltage drop measurements made in both current modes, it was then possible to calculate the effective interface resistances R_1 (wire-to-plate), R_2 (wire-to-screw), R_3 (screw-to-plate), and R_n (total connection resistance). This technique was used to investigate the effect of screw torque on these interface resistances, and to make comparative tests between copper and aluminum wire.

From these tests, which were conducted on three CO/ALR receptacles and one old style receptacle, the following observations were apparent:

7.1 On both CO/ALR and old style receptacles, the interface resistance initially established between wire and plate (R_1) is significantly higher than either R_2 (wire-to-screw) or R_3 (screw-to-plate) and may be up to 3 times greater than the sum of R_2 and R_3.

7.2 On both style receptacles R_1 appears to be more sensitive to screw torque than either R_2 or R_3. This is probably due to the fact that the interface between wire and plate is established essentially by normal or compressive force whereas a wiping motion is involved at the screw-to-wire and screw-to-plate interfaces.

7.3 Compared to the old style receptacle, the CO/ALR receptacles appear to provide consistently lower connection resistances at all torque levels.

7.4 Compared to an aluminum wired connection, a copper wired connection provided substantially lower wire-to-plate resistances whereas R_2 and R_3 appear to be essentially equivalent for both conductors.

8. CURRENT CYCLE TEST

As a pilot test, one old style receptacle was wired with #12 aluminum and subjected to repetitive cycling at a test current of 40 amperes. Each cycle consisted of 12 minutes "on" and 6 minutes "off." The technique described above was used to make periodic measurements of the connection interface resistances. This test was stopped after 905 cycles due to visible failure of the connection (charred plastic around terminal).

From the data, it appears that the following conditions led to the ultimate failure of the connection:

8.1 The interface resistance between the wire and the plate (R_1) was initially quite poor (1.2 milliohms) and increased by a factor of approximately 40 during the test.

8.2 Although R_2 (wire-to-screw resistance) was initially low, it also increased by a factor of 5 during the test.

8.3 The screw-to-plate resistance (R_3) showed a decrease of approximately 40 percent during the test.

8.4 Due to the combined changes in R_1, R_2, and R_3, the effective connection resistance, R_n, also increased by a factor of 4. Deterioration of the receptacle body began when R_n reached a value of approximately 1.4 milliohms.

9. MOTION MEASUREMENTS

A pilot experiment, using holographic techniques, was conducted in an attempt to measure the relative motions that occur in a binding screw connection during thermal stress. In this experiment the dynamic image of a connection (during heating) was compared optically with a hologram of the same connection at ambient temperature. The experiment produced a visible pattern of interference fringes which changed in frequency, location, and orientation as the connection changed temperature. After several thermal cycles, the fringe pattern appeared to return to its initial configuration except around the wire insulation. This would seem to indicate that the thermal cycling caused a permanent change in the plastic insulation but not in the mechanical components of the connection. Time-lapse photographs have been made of the fringe patterns but a method for translating these patterns into quantative measurements has not been developed.

10. LABORATORY TESTS ON DEVICES FROM HOUSE IN HAMPTON BAYS, NEW YORK

Tests were made on several devices removed from the site of a residential fire in Hampton Bays, New York. The results of these tests were summarized in a special report dated May 29, 1974, and in the Third Quarterly Report (Engineering

Phase of the Aluminum Wiring Report, pages 13-16). However, a few comments may be made as follows:

Of the 6 receptacles tested (24 screw terminals) 12 connections were loose to the point where it was difficult if not impossible to measure a stable value of resistance. This seemed to be more true of receptacles wired with the heavier gauge #10 wires than those wired with #12 wire. It could be inferred that at least part of the problem is the increased stiffness of the heavier wire which is more likely to be loosened when stuffed into a receptacle box.

Torque ranged from 14 in-lbs down to a point so low that measurement could not be made with ordinary equipment. Overheating of terminals, of course, was evident where connection resistance was appreciably above normal.

Workmanship varied from good to very poor but there was not sufficient field information to indicate how this compares with typical house wiring.

Micro examination of the overheated terminals showed large amounts of insulating oxides and air gaps in the interface. These also showed areas where the brass plating was missing under the steel screws and additionally the presence of iron oxide. There was also some evidence of very localized arcing between steel screw and aluminum wire.

11. EXTENDED LABORATORY TESTS

In addition to the preliminary or pilot tests discussed in Section 2, a series of more extensive tests have been initiated and are now in progress or completed. These tests were not intended to be long term performance tests, but were designed primarily to investigate some of the possible factors involved in connection failures or to investigate the effectiveness of currently available fixes.

12. CURRENT CYCLE TEST

Ten old style receptacles with steel screws and with poor break-off tab characteristics are undergoing continuous current cycle testing. These devices are wired with a non-approved aluminum conductor (#12 AWG) and with screw torques of 6 inch pounds. The current cycle consists of 12 minutes "on" and 6 minutes "off" at 40 amperes. Initial interface resistance measurements were made on all 40 connections, and at periodic intervals new measurements are made. The temperature of the connections is not monitored continuously, but is checked periodically with a thermocouple probe. The test rack is situated in open air. The purpose of this experiment is to investigate the behavior of the various connection interfaces during cycling and during any failures which might occur.

At this time, all receptacles have passed more than 4800 cycles without any visible evidence of overheating such as melted insulation, smoke, or charred plastic around the terminals. On one receptacle (#9), however, the screws on the "white" side have reached temperatures of 149° and 153°C. The screw temperatures on three other connections have risen to between 100° and 120°C.

From the data accumulated to date from this test, the following observations have been made:

12.1 The interface resistance between the wire and the contact plate is highly unpredictable and erratic. This resistance was found to vary by several orders of magnitude both initially and during cycling. Also, in most of the connections, this resistance is so high that most of the current is forced to flow through the screw. After 4300 cycles, the average wire-to-plate resistance for 40 connections is 13 milliohms.

12.2 The interface resistance between the wire and the screw does not exhibit the large erratic changes that are characteristic of the wire-to-plate interface. In most connections, however, this resistance does increase measurably with cycling. After 4300 cycles, the average value of this resistance for 40 connections is 0.24 milliohms.

12.3 The resistance between the screw and plate appears to fluctuate more and is generally higher than the wire-to-screw resistance. In addition, on two "white" side connections, this resistance has shown a dramatic increase during the test, causing a substantial increase in connection temperatures. The average value of this resistance after 4300 cycles is 0.66 milliohms for all 40 test connections.

13. HEAT CYCLE TEST

Sixteen old style receptacles are undergoing continuous heat cycling tests. In this test, the receptacle type, the aluminum wire type, and the screw torques are the same as in the current cycle test. In the heat cycle test, however, the connections are not subjected to cyclic current flow. Instead, the connections are subjected to repetetive thermal cycles of four minutes duration. During each cycle, the connections are heated for 1 1/4 minutes and cooled for 2 3/4 minutes by individual air streams. This subjects each connection to a thermal excursion of approximately 65°C (35° to 100°C) every four minutes. Periodically the test is stopped long enough to make voltage drop measurements of the connections, and from these the various interface resistances are calculated.

After 9255 cycles, three of the 32 connections in this test have essentially "failed" in that their effective resistances, R_n, have increased from .91, .96, and .98 milliohms to 1.7, 2.5, and 3.7 milliohms respectively. If these connections were subjected to a 40 ampere current, they would undoubtedly overheat.

A comparison of the data from the heat cycle test with those from the current cycle test show very similar connection behavior. In both tests, the data for those connections which have "failed" or appear to be approaching failure, show that the current path from wire-to-plate becomes ineffective quite rapidly. This forces the performance of the connection to be almost entirely dependent upon the wire-to-screw interface and the screw-to-plate interface. If either or both of these interfaces increase in resistance, it causes an increase in the effective connection resistance and an increase in connection temperature.

Combined data from the heat cycle and current cycle tests appear to show a difference in behavior between "white" and "brass" side connections. On the white side, both failures appear to be due to an increase in resistance from screw-to-plate, whereas on the brass side, the failures appear to be due primarily to an increase in the wire-to-screw resistance.

14. SIMULATED WALL TEST

Twelve receptacles of the same type used in the heat and current cycle tests are undergoing current cycle tests in a simulated wall. These receptacles are wired with #12 aluminum wire at screw torques of 12 inch pounds. The receptacles are mounted in metal wall boxes with metal face plates. A thermocouple is cemented to one screw head on each side of each receptacle and brought out to recording equipment. Six of the boxes are mounted in wall sections that are insulated with glass fiber batting and the remaining six are mounted in un-insulated sections. The receptacles are wired in series as they would be in a typical branch circuit, and are being subjected to a test current of 15 amperes which is cycled "on" for 12 minutes and "off" for 6 minutes. The purpose of this test is to obtain thermal profiles of connections in typical wall installations and to compare their behavior with those tested at higher currents in open air.

This test has now exceeded more than 500 cycles, and there has been no significant change in the connection temperatures. During cycling, the average thermal excursion measured at the screw head is approximately 10°C (33° to 43°C).

15. POST-INSTALLATION TORQUE TESTS

It has been suggested that one possible cause of receptacle failures in the field might be due to screws that are loosened when the receptacle is pushed into the wall box. To explore this factor, a series of post-installation torque tests have been made on two types of old receptacles and six types of CO/ALR receptacles. In these tests, a standard metal wall box with removable sides was rigidly attached to a test stand and two lengths of #10, 2-wire aluminum cable were installed and clamped in the box in a conventional manner. The wires were then stripped and connected to the test receptacle. In an attempt to simulate actual installation practices, the screw connections were made in a hurried fashion, and no attempt was made to form perfect wire loops. All screws were then tightened to a known torque and the receptacle was then pushed into the box and secured by its mounting screws. At this point, the sides were removed from the box and the residual torque on each screw was measured and recorded. For each receptacle type, this procedure was repeated three times each at initial torque levels of 6, 10, and 14 inch pounds. For each test trial, new wire loops were made, and a new receptacle was used.

The results of these tests to date can be summarized as follows:

15.1 On both old style receptacles tested, the measured post-installation screw torques were highly variable, particularly at the 6 and 10 inch pound test levels. At the 6 inch pound test level one of the 24 test connections was totally loose, and 11 connections had residual torques of less than 3 inch pounds. At the 14 inch pound test level the average residual torque on both non-CO/ALR receptacle types was 10 inch pounds.

15.2 At all three test levels, the CO/ALR receptacles gave consistently higher post-installation measurements than the old styles that were tested. Out of 60 trials at 6 inch pounds there were no totally loose connections, and even the poorest performer, had an average residual torque of 4.1 inch pounds. At the highest test level (14 inch pounds) all types tested provided average residual torques of 13 to 13.5 inch pounds.

16. CO/ALR RESISTANCE MEASUREMENTS WITH COPPER AND ALUMINUM CONDUCTORS

For comparative purposes, interface resistance measurements have been made on six types of CO/ALR receptacles with #12 copper and #12 aluminum wire. On each type receptacle, a total of 16 connections were tested; four with each conductor at 6 inch pounds and four with each conductor at 12 inch pounds. In each test configuration, half of the connections were on the "white" side of the receptacle and half were on the "brass" side. A new receptacle and new wire loops were used for each test.

The results of these tests can be summarized as follows:

16.1 At both torque levels all of the receptacles tested provided very low and very consistent connection resistance measurements for both conductors. At 6 inch pounds, the average effective resistance, R_n, for 24 connections was .00013 ohms for copper and .00015 ohms for aluminum. At 12 inch pounds, the average effective resistance for 24 connections was .00012 ohms for copper and .00014 ohms for aluminum. From a practical standpoint, these small differences are negligable.

16.2 Compared to similar data on old style devices, the data on the CO/ALR receptacles shows a significant reduction in all of the critical interface resistances. The most dramatic improvement, however, is in the wire-to-plate resistance. For the old style receptacle that is being used in the current and heat cycle tests, the average initial wire-to-plate resistance was .00310 ohms at 6 inch pounds screw torque. At the same torque level, the average wire-to-plate resistance for the CO/ALR receptacles was .00043 ohms - nearly an order of magnitude lower. This results not only in lower net connection resistances, but also in a better distribution of current within the CO/ALR connections.

16.3 Although the CO/ALR connections do show slight differences in resistance at the 6 and 12 inch pound torque levels, they appear to be considerably less sensitive to screw torque than connections on old style receptacles.

17. SPECIAL WASHER TESTS

One device manufacturer has developed a special device for possible use in aluminum wired branch circuits. This device consists of a "U" shaped metal washer which has a pattern of sharp "spikes" raised on both its top and bottom surfaces. In a typical binding screw connection, this washer is meant to be inserted between the wire loop and the contact plate so that when the screw is tightened, the spikes will penetrate the surfaces of the wire and the contact plate, providing a low resistance connection that is mechanically stable.

To test the initial effectiveness of this device, torque versus resistance tests were made on three types of non-CO/ALR receptacles both with and without the washer. Tests were performed at 6 and 10 inch pound screw torques, using #12 gauge ECH19 aluminum as the test conductor.

On two of the test receptacles the washer reduced the wire-to-plate resistance by factors of from 2 to 3 at both torque levels. This improvement was also reflected to a lesser extent in the total connection resistance. On the third test receptacle, the washer made only a very slight difference in the wire-to-plate or the total connection resistance at either torque level.

Further tests of this device are not planned at this time since the manufacturer has recently announced that he does not intend to produce or market it.

18. INDIUM DIFFUSION EFFECTS ON CO/ALR DEVICES

In studies conducted at Bell Laboratories, it has been shown that indium interdiffuses readily with copper or copper based metals and forms an intermetalic interface which is extremely hard and brittle compared to the original indium. On six of the seven approved CO/ALR receptacles, the brass screws are plated with indium to provide improved connections to aluminum. On these components, the indium-copper diffusion process will undoubtedly occur in due time.

To test the effects of this phenomenon, fifteen each of two types of indium plated CO/ALR receptacles are being prepared for extended current cycle testing. Within each test group, both aluminum and copper wired connections will be tested. With both types of conductors, new connections will be tested along with connections in which the diffusion process has already taken place. (The latter connections are being aged for five days at 150°C to accelerate the diffusion process.) During the current cycling phase of this experiment, connection temperatures and resistances will be monitored periodically.

19. SCREW ROTATION MEASUREMENTS

An investigator for an aluminum manufacturer has reported that he has measured a small counter-clockwise rotation (loosening) of binding screws on receptacles that are subjected to repetitive current cycling. Although we believe that these results are questionable, an experiment to investigate this possibility further is now being conducted at NBS. Time-lapse photographic techniques are being used to determine if relative motion does occur between the screw heads and contact plates on ten receptacles. No results from this experiment are available at this time.

20. CURRENT TRANSIENT EFFECTS

It has been reported by Mr. Abbott of Battelle, that the performance of screw terminations appears to change significantly when subjected to high current transients such as occur with inductive or incandescent lighting loads. At NBS, preliminary experiments along this line have not shown any conclusive results. A controlled experiment to investigate this effect further is now being planned.

TECHNICAL SUMMARY OF ALUMINUM
WIRING RESEARCH CONDUCTED BY THE
CENTER FOR BUILDING TECHNOLOGY (CBT)

1. PURPOSE AND SCOPE OF REPORT

This report contains a brief summary of the aluminum wiring research conducted by the Center for Building Technology (CBT) between January and August 1974. It was prepared at the request of the Consumer Product Safety Commission.

2. IDENTIFICATION OF CONDITIONS WHICH CAN LEAD TO FIRES

Experiments are being conducted to identify the conditions needed for an electrical outlet to ignite building materials.

The initial experiments were conducted with a receptacle mounted in open air on a lab bench. A current of 15 amperes was passed through a totally loose binding head screw connection and vibration of the wire was induced to initiate arcing. Combustible materials, such as paper from thermal insulation, were placed over the loose screw. The results showed that combustible materials could be ignited readily under these conditions using either aluminum or copper wire.

During these initial experiments, it was observed that a "glow" condition could be initiated between aluminum or copper wire and steel binding head screws. The glow, which produced overheating, was initiated after a small wire disturbance and sustained itself thereafter without additional wire disturbance. The glow could not be obtained with either aluminum or copper wire in contact with brass screws.

Additional experiments were conducted using a test wall section constructed of wood 2 x 4 studding, wood paneling on the interior side, and celotex on the exterior side. Mineral wool insulation was used in the wall section interior. The duplex receptacle, placed in the wall section, was wired with copper or aluminum non-metallic cable (sizes #14 or #12 AWG, respectively). The white wire and ground wire were attached with a 12 in-lb torque and the black wire was initially attached using 2 in-lb torque. To obtain a loose wire, the screw was loosened two turns from the 2 in-lb position. The receptacles were subjected to 15 amperes of AC current from a 120 volt building supply and the temperature of the receptacle was measured using thermocouples. The wire was disturbed slightly at the start of the test to initiate the glow condition (with steel screws), but no other disturbance was used during the test.

The maximum temperatures measured under the test conditions were on the black wire side breakoff tab. The temperature obtained at this point with aluminum wire and steel screws was 748°F while that for copper wire and steel screws was 737°F. Both aluminum and copper wire on brass screws produced temperatures of about 113°F. It should be emphasized that the high temperatures observed with steel screws and both copper and aluminum wire occurred as a result of the glow condition. Both copper and aluminum wire with steel and brass screws were shown to produce high temperatures if continuous vibration to induce arcing was used.

Although actual ignition of the wall materials did not occur during these tests, extensive charring of the wood paneling as well as decomposition of the PVC wire insulation and the plastic of the receptacles was observed. The high temperatures observed are believed, however, to be sufficient to induce ignition if combustible materials are close to the glow or the arc.

These results show that loose electrical connections with steel binding head screws and copper or aluminum wire can maintain extremely high temperatures and relatively high heat energy generation with conducting currents of 15 amps and that these high temperatures can be obtained without a continuous wire disturbance.

Further experiments in which the black wire screw was tightened to provide a snug fit (by tightening to 2 in-lb and backing off 1/8 turn) between the connector plate, wire and screw head, have shown that the glow between steel screws and copper or aluminum wire can be initiated and sustained under these conditions. It has also been determined that the glow condition is not dependent upon the level of applied current or voltage. For example, glows have been started at 3-4 volts and with currents of less than one ampere.

One fire has been started in the test wall section. The conditions were as follows: aluminum wire (#10 AWG), brass screws (in loose connection) and induced vibration to induce arcing. The fire is believed to have been due to the ignition of gases resulting from the decomposition of the PVC wire insulation. We believe that one possible fire starting mechanism can result by inducing an arc as gaseous components are being driven off by an overheated terminal. The overheated terminal, for example, might arise from the glow condition mentioned earlier.

3. COMPARISON OF ALUMINUM, COPPER AND COPPER-CLAD ALUMINUM WIRE BY SALT SPRAY EXPOSURE

An experiment is being conducted to compare the performance of terminations made with aluminum, copper and copper-clad aluminum wire to both steel and brass screws during exposure to a 5% salt spray environment. Connections were made with both 6 and 16 in-lb torque. IR drops across various points in the wired devices are used to measure the performance. Exposure to a corrosive atmosphere such as salt spray cannot be used to predict an expected service life but it can be very useful in comparing various specimens.

The results to date indicate that aluminum terminations with both steel and brass screws increase in IR drop at a much faster rate than copper or copper-clad terminations as a result of salt spray exposure. For example, after 100 hours of exposure, aluminum-steel terminations increased 240% and 58% in IR drop relative to initial measurements at 6 and 16 in-lb torque, respectively. Aluminum-brass terminations, after 100 hours, at 6 and 16 in-lb increased 21% and 19%, respectively. All copper and copper-clad terminations showed little or no increase in IR drop after the same exposure.

4. CHARACTERIZATION OF CO/ALR RECEPTACLES

Samples of five types (4 with indium and 1 without indium) of CO/ALR receptacles were evaluated in the as-fabricated condition. Samples of three types (all with indium) were evaluated metallographically after exposure to oven heating at 150°C for six days.

Metallographic examination showed that, following the heat aging, all the indium on the devices had completely diffused to form an indium-brass compound with a hardness equivalent to that of tool steel. The indium plating on specimens not subjected to heat aging showed no signs of diffusion.

A preliminary test was conducted to determine if the serrations on the connector plate of an indium plated CO/ALR receptacle would penetrate the oxide on aluminum with 6 in-lb torque. A three-quarter loop geometry was used and the specimen was examined metallographically. It was determined that the serrations on the connector plate do not fracture the aluminum oxide film on the wire under the conditions used.

5. CHEMICAL ANALYSIS OF RECEPTACLE COMPONENTS

Nineteen electrical receptacles were analyzed to determine the compositions of the binding head screws and the connector plates. For the receptacles with steel screws, the percent carbon in the screws was determined and the percent copper in brass screws was determined. The carbon content in steel screws from various type receptacles varied from 0.048 to 0.104 weight percent. The percent copper in brass screws was determined to vary from 64 to 74 percent in the various receptacles. The percent copper in brass connector plates varied from 63 to 90 percent in the various receptacles. Of the five CO/ALR devices analyzed, two contained indium plating on the plated screws and the plated connector plate, one contained tin plating on the plated screws and connector plate, one contained tin plating on the plated screws and indium plating on the connector plate, and one contained an indium-tin mixed plating on the plated screws and on the connector plates. Other plating materials found on various non-CO/ALR devices included zinc and nickel.

6. PRELIMINARY STUDY OF COMPRESSION CONNECTORS

Two types of compression connectors were connected to aluminum #10 AWG wire, mounted in an epoxy matrix, and viewed microscopically. The purpose of the preliminary study was to determine the type of connection the devices make to aluminum wire. Compression connectors are being proposed as a possible means to reduce the problems observed with aluminum terminations.

One compression connector studied consisted of a cylinder of tin plated brass with a grooved bronze sleeve inside the brass cylinder. The aluminum wire was placed inside the bronze sleeve and compression applied with the tool provided by the manufacturer. A cross section of the connection showed that good metal-metal contact was made between the bronze and the wire but that the thickness of the wire at the point of compression was reduced by a factor of about five compared to the non-compressed wire.

The second compression connector consisted of a trough shaped aluminum alloy member into which aluminum wire was pressed. A cross section of this connection showed that good metal-to-metal contact was achieved.

The performance of compression connectors under current carrying conditions has not been determined.

7. PENETRATION OF PLATE SERRATIONS AND SCREW HEADS INTO THE ALUMINUM OF COPPER CLAD ALUMINUM WIRE

An experiment was conducted to determine if, in making connections to copper-clad aluminum wire, connector plate serrations or the friction of the screw head would result in direct contact to the aluminum by penetrating the copper cladding. Three types of screws were studied. Two of the screws were undercut and one was not. The screws were tightened to torques varying from 2 to 18 in-lb before loosening the screws and looking at the wire surface with a microscope.

It was found that undercut screws did penetrate through the copper and into the aluminum at torque levels above 6 in-lb. Screws which were not undercut did not make contact with the aluminum up to torque levels of 16 in-lb. Serrations on connector plates penetrated into the aluminum at torque levels of 8 in-lb and greater.

8. INTERFACE STUDIES OF RECEPTACLES FROM THE HOUSE IN HAMPTON BAYS, NEW YORK

Metallographic examination and chemical analysis are being performed on two aluminum wired receptacles which were removed from circuits in the house at Hampton Bays, N. Y. The house had experienced a fire that was attributed to aluminum wiring. Both receptacles being studied contained signs of overheating (decomposed PVC wire insulation and bakelite) and both contained steel binding head screws.

The interfaces between the wire and overheated screws on these devices are being studied at magnifications up to 1000x. The wire/screw interface is particularly important because prior studies have shown that this is the path of greatest current flow. These later studies show that the interfaces contain material which differs in appearance from the wire and the screw. Preliminary results from electron microprobe analysis shows that the extraneous material in one overheated interface consists of various amounts of aluminum and zinc oxides and compounds of iron, silicon, maganese and copper. Copious quantities of chloride have also been detected in the interface materials. The chloride is believed to originate from the decomposition of the PVC wire insulation because sodium and potassium, which would accompany chloride from a salt environment, were not detected. There are strong indications that oxidation of the iron in the steel screws may be initiating mechanism for the overheating of the electrical devices from the Hampton Bays house.

The interfaces between the wire and the brass connector plate are also being studied. The wire/plate interface of the overheated terminal of one of the receptacles shows that the wire and plate are no longer in direct contact. But aluminum has been detected on the connector plate surface which indicates that the wire and plate were in contact at some point in time. The connector plate of this same receptacle is broken. We believe the plate broke as a result of high pressure applied in tightening the screw during installation. Another interesting finding is that zinc has been depleted from the brass connector plate to a depth of about 25μ. The depleted zinc has formed zinc oxide and is located in the interface between the wire and the plate.

9. TESTS ON RECEPTACLES INSTALLED IN A WALL STRUCTURE

Thirty-six receptacles, installed in a laboratory wall structure, are being cycled at 3 1/2 hours ON and 1/2 hour OFF using 15 amperes and 120 volts. The receptacles contain both steel and brass screws and are wired with both copper and aluminum wire at torque levels of 2, 6 and 12 in-lb. The torque levels were applied after installing the devices in metal boxes. During the power cycling, the device temperature, the ambient temperature in the box and the ambient temperature in the wall are being monitored. The receptacles are being removed periodically from the wall and studied metallographically to identify the interface changes which lead to overheating.

At present, only one device exhibits overheating. This device is wired with aluminum to brass screws at 2 in-lb torque. After 30 cycles, the temperature on the breakoff tab of this device has reached about 135°C and is exhibiting a steady increase.

At the end of twenty cycles, twelve receptacles were removed for metallographic examination. These receptacles have been mounted in epoxy and some of them have been sectioned. However, no conclusive metallographic results have yet been obtained.

10. FUTURE STUDIES

Additional studies planned for the near future are summarized below.

10.1 Fire Starting Mechanisms

Additional studies are planned with plastic boxes in the fire starting experiments. Also, experiments will be performed to determine if the volatile products resulting from overheating can be ignited by induced arcing.

10.2 Characterization of the Glow Phenomenon

A test apparatus has been constructed to further characterize the glow phenomenon that has been observed with loose steel screws.

10.3 Measurement of Oxide Resistance

In Section 2, it was reported that aluminum and copper wire terminations with brass screws were not observed to overheat, even when the screw was loose. Other findings, however, indicate that the aluminum termination to brass would be expected to produce more resistance heating than the copper to brass termination. Additional studies will be conducted to clarify the test results.

10.4 Salt Spray Exposure

The salt spray experiment described in Section 3 will be continued.

10.5 Interface Studies of Receptacles from the House in Hampton Bays

The metallographic and chemical analysis studies described in Section 8 on the receptacles from the Hampton Bays house will be continued.

10.6 Wall Structure Receptacles

The metallographic and chemical analysis studies described in Section 9 on the receptacles in the laboratory wall structure will be continued.

10.7 Metallographic Analysis of a CO/ALR Receptacle with Indium Plating

An indium plated CO/ALR receptacle, which has been subjected to long-term power cycling at Underwriters' Laboratories (UL), will be studied metallographically. The purpose of the study will be to determine if the indium has been converted to the hard alloy previously described. Since UL has not observed overheating in their CO/ALR devices under test, the presence of converted indium would imply that the alloy formation after installation is not deleterious to performance.

10.8 Inspection of Aluminum Wired Devices at Military Bases

A number of military bases have utilized aluminum wiring for base homes and buildings. Several of these bases are now experiencing varying degrees of overheating of the devices. Military personnel have agreed to NBS personnel inspecting the homes. Therefore, we will visit one or two bases in the near future to obtain information that will be useful in the laboratory study. In particular, the type of wire of devices, the workmanship, the climate, the device temperature, the termination resistance and other information will be obtained. Devices containing signs of overheating will be retrieved for further laboratory studies.

Summary of UL Test Results

1.0 Introduction

In 1972 UL concluded major activities resulting in the upgrading of requirements for solid aluminum conductors in AWG sizes 12 through 8, and for wiring devices employing binding head screws (rated 15 and 20 amperes) intended for direct connection to aluminum wire. In addition, UL has developed and is implementing new test programs for pressure wire connectors intended for use with aluminum, aluminum-copper and copper wire. Included in the latter program are screw tightened cable and terminal connectors, crimp type cable and terminal connectors, and manually tightened cable connectors (wire nuts). To aid NBS in its studies, UL has provided NBS staff members with copies or summaries of much of the source data accumulated during its aluminum conductor, CO/ALR devices (switches and receptacles), and wire nut test programs. The following sections of this report are summarizations of test results in these three programs.

2.0 Aluminum Conductor Test Program

In its initial investigation of aluminum conductors, UL tested 23 aluminum conductors (#12 AWG), one semi-annealed aluminum conductor, and one #14 AWG copper conductor. The physical properties of the aluminum conductors ranged from 15 to 26 KSI ultimate tensile strength and from 2% to 28% elongation. Final evaluation of a conductor was based on its performance during approximately 900 cycles of current cycle testing at current levels of 40, 30, 25 and 20 amperes. For these tests a commercial receptacle with steel plated screws was used, screws were torqued to 6 inch pounds, and 50% of the wire loops were formed in the reverse (counter-clockwise) direction. Five samples of each conductor were tested at each current level. The cycle rate during these tests was 3 1/2 hours on, 1/2 hour off, and a temperature of 175°C, measured at the break-off tab, was used as a failure criterion.

In evaluating each conductor's performance a weighing factor of one was assigned for any failure at 40 amperes, a factor of two for any failure at 30 amperes, and a factor of three for any failure at 25 or 20 amperes. For each conductor, the number of failures at each current level was multiplied by the weighing factor and the total sum was used as a rating number for the conductors. Only those conductors with numerical ratings of 2 or less were subsequently approved for branch circuit use. Ten of the 23 aluminum conductors tested met this criterion.

To test the effects of other factors each conductor was also subjected to current cycle tests in eight additional test configurations. These tests involved additional levels of screw torque, variations of screw material (brass and aluminum) plus tests with receptacles from three additional manufacturers. Two aluminum conductors were also tested with and without oxide inhibitor. Three of the configurations at 20 and 25 amperes are still being tested and have now exceeded 4300 test cycles.

In summarizing the above tests, UL points out the following observations:

1. On one device, where comparable data was available, steel screws showed a significantly higher failure rate than brass screws.

2. The data on two other devices (one employing brass screws and one employing steel screws) showed a slightly higher failure rate for the device with brass screws. UL attributed these apparent differences in performance to differences in terminal geometry and weight.

3. Twenty-eight failures have occurred at the lower test currents (20 and 25 amperes). Twenty-five of these failures were with aluminum conductors which did not meet UL's acceptance criteria.

4. The variable torque tests demonstrated that screw torque is a significant factor in determining connection performance. The data showed that as torque was increased, average connection temperatures as well as temperature variations decreased.

5. The application of oxide inhibitor to screw terminals proved beneficial to long term performance.

2.1 Aluminum-Alloy Recognition Program

Based on the test experience described above, UL finalized it's Aluminum-Alloy Recognition Program in September, 1972. This program defines the specific tests that an aluminum conductor must pass in order to be approved as follows:

1. Fifteen samples of No. 12 AWG, Type TW aluminum alloy wire, fabricated from the aluminum alloy rod under investigation, will be secured to the Leviton Cat. No. L5320 SPS Duplex Receptacle with a 3/4 wrap and torqued to six inch-pounds. Thermocouples are to be placed on the breakoff strap. These samples are then to be connected to a 40-ampere constant-current supply and subjected to 500 cycles of operation with each cycle consisting of 3 1/2 hours "on" and 1/2 hour "off".

2. The results are acceptable if at least 12 samples (13 if a single failure occurs, see paragraph 2.4) operate below 175°C with each temperature profile exhibiting termination stability.

3. Where the temperature profiles appear not to have stabilized within the 500 cycles, the test will be extended to 1000 cycles with the same acceptance criteria applicable at the end of that time also.

4. In addition, where a single failure occurs within the first 50 cycles of test, the failure will not be counted in the over-all performance rating. The device will be removed and replaced by two new samples.

5. The conductor must have an ultimate tensile strength of from 15 to 22 KSI and a minimum elongation of 10%.

In addition to the above, the Recognition Program also specifies reporting, inspection, and labelling procedures to insure that the properties of an approved alloy are maintained and reproduced by the manufacturer. Nine manufacturers now have aluminum conductor materials that have been approved by UL under this program.

3.0 CO/ALR Test Program

The detailed performance requirements that a receptacle or snap switch must meet to be listed by UL for use with aluminum wire are defined in UL Bulletins dated October 13, 1971, September 29, 1972, and November 24, 1972. Generally, the test program requires that the binding screw terminations exhibit low and stable temperature profiles during 500 cycles of exposure to test currents representing 266 percent and 353 percent of the device current rating (for a 15 ampere device).

The complete CO/ALR test consists of the following basic parts:

1. Heat cycling with wire disturbance - 40 ampere test current, #12 aluminum wire.

2. Heat cycling with wire disturbance - 53 ampere test current, #10 aluminum wire.

3. Heat cycling with vibration - 53 ampere test current, #10 aluminum wire.

4. Environmental cycling (temperature and humidity) - rated current, #12 or #10 aluminum wire.

5. Stripping - torque test - 16 inch pounds.

Wiring devices rated at 20 amperes are not subjected to test 1. Failure criteria for the heat cycling tests are either a 100°C rise in the terminal temperature or a temperature stability factor greater than 10. Failure criteria for the environmental test is a 30°C rise in terminal temperature while carrying rated current. In all cycling tests, the devices are wired with either of two non-listed aluminum conductors that were ranked low by UL's conductor tests, and screws are torqued to 6 inch pounds. Test currents are cycled on for 3 1/2 hours and off for 1/2 hour.

At present, seven manufacturers have one or more receptacles that are listed under the CO/ALR program and five manufacturers have CO/ALR listed switches.

3.1 Summary of CO/ALR Test Data

In May, 1974, UL provided NBS with copies of much of the source data accumulated on the CO/ALR program through April, 1974. Included were the following:

1. Temperature data on 13 receptacle types tested at 40 amperes with wire disturbance.

2. Temperature data on 14 receptacle types tested at 53 amperes with wire disturbance.

3. Temperature data on 13 receptacle types tested at 53 amperes with vibration.

4. Temperature data on 3 switch types tested at 40 and 53 amperes with wire disturbance.

5. Temperature data on two receptacle types tested at 53 amperes with distorted loops and wire disturbance.

Although UL requires that the devices pass only 500 cycles of heat testing, most if not all, of the CO/ALR tests are being extended indefinitely to obtain additional long-term performance data. For this reason, the above results include data on many devices that, in April 1974, had experienced between 1500 and 4300 test cycles. Some of these devices have now exceeded 5000 test cycles.

With the above data, UL did not provide any summarizing comments or conclusions. The following statements or comments are based on our own review of the data.

1. The data on the 40 ampere heat cycle test with wire disturbance shows one apparent failure (at 100 cycles) out of the 78 receptacles on test in this extended test. In discussions with UL staff it was learned that this was not a true failure but an overheating of the receptacle caused by the failure of a nearby line connector. To qualify this "failure" six additional receptacles of the same type were added to the test. These are continuing to perform without any evidence of problems.

   Temperature readings after extended cycling (1500 to 4300 cycles) show no significant increase in connection temperatures on the devices under test.

2. The data on the extended, 53 ampere heat cycling test with wire disturbance shows 4 failures out of the 84 receptacles on test. All of these occurred on one manufacturer's type which did not receive UL approval. In this test there does appear to be a slightly upward trend in the temperature profiles of some devices with extended cycling. With one exception, however, all of the types on test are performing well below UL's failure criteria. One manufacturer's model exhibited relatively high terminal temperatures even in the early stages of the test and, even though it passed the 500 cycle requirement, at approximately 3300 cycles several terminals show thermal rises of greater than 90°C.

3. Data on the 53 ampere heat cycle test with vibration shows no failures among the 13 types under test during the required 200 test cycles. With extended cycling, however, the data shows one failure after 1992 cycles. On this particular receptacle type, one terminal out of the eight on test showed a thermal rise of 105°C. At the same point in the test, the average temperature rise of the remaining seven terminals was 73°C.

   The data from this test also shows higher than average thermal profiles on the same type receptacle that exhibited the highest terminal temperatures in the 53 ampere heat cycle test. At these high test currents, the performance of this particular receptacle appears to be somewhat marginal.

4. In the UL data package, test data on only 3 switch types were included although five manufacturers now have two or more switch models which are CO/ALR listed. Presumably, test data on the other switch types are available but have not been requested at this time.

   The switch data that we have reviewed shows no failures at 40 or 53 amperes for two of the types during 2000 to 3000 test cycles. At both current levels, average temperature profiles of these two types appear to be stable. On the third type, one sample out of six failed the 40 ampere test at 150 cycles and three samples out of six failed the 53 ampere test after approximately 3000 cycles. Apparently this switch was made by the same manufacturer whose receptacles appeared marginal in the 53 ampere tests.

5. Although such tests are not part of the CO/ALR requirements, UL subjected two receptacle types to 53 ampere heat cycle testing with wire disturbance and distorted wire loops. The types chosen for this test represented, in UL's opinion, the extremes in device construction. The devices represent CO/ALR devices as follows:

a. With and Without wire guides

b. With and without indium plating

c. With and without lubricated screws

d. With and without contact plate topography

Three samples of each device was tested at screw torques of 6, 8, and 10 inch pounds.

The data shows that on one receptacle type one failure occurred at 6 inch pound after 123 cycles and another at 8 inch pounds after 95 cycles. On the second type, one sample failed at 6 inch pounds after 666 cycles.

At the 10 inch pound torque level neither type has shown any failures after 3000 to 4000 cycles. The device which showed early failures in this test at both 6 and 8 inch pound is apparently a type which does not employ indium plating or serrated contact plates but which does employ wire guides and lubricated screws.

Although at this time it is not known how well the UL accelerated performance tests for CO/ALR devices relate to actual long-term field performance, it should be pointed out that, in equivalent laboratory tests, the performance of the CO/ALR devices show a dramatic improvement over the old style devices. This can be seen by comparing UL's aggregrate data from its aluminum conductor tests with data from the CO/ALR test program. In the conductor tests, which involved three types of old style receptacles and twenty-six conductors, approximately 60 percent of all test samples failed in less than 500 cycles when subjected to 40 ampere heat cycling, without wire disturbance and at 6 inch pound screw torques. Also in the aluminum conductor tests, approximately 9 percent of the samples have failed in the extended heat cycle tests at test currents of 20 and 25 amperes and 6 inch pound torques. By comparison none of the approved CO/ALR receptacles have failed in UL's extended heat cycling tests with wire disturbance, at test currents of 40 and 53 amperes and screw torques of 6 inch pounds.

4.0 Test Program for Pressure Cable Connectors (Wire-Nuts)

UL has separate listings and test requirements for the following classes of wire nuts:

1. Copper-to-copper connections only.

2. Aluminum-to-aluminum connections only.

3. Aluminum-to-copper connections, "dry locations only."

The mechanical tests for all three classes are the same and are defined in UL Standard 486. The primary distinction between the three classes is in the heat performance tests. For "Copper Only" wire nuts, the devices must pass a static heating test. For "Aluminum Only" wire nuts the devices must pass the same static heating test plus 42 cycles of current cycling at 25 amperes. For "Aluminum-Copper" wire nuts the devices must pass the static heating test plus a 500 current cycle test at 25 amperes. Failure criteria for the AL-CU test is a 175°C rise in bulk temperature.

At the present time, six manufacturers have wire nuts that are listed by UL for "Aluminum-Copper" applications. These listings involve many catalog or model numbers for each manufacturer. At this time we do not have complete test data on all of these devices, however, UL has supplied NBS with summaries of data on nine models from three manufacturers. These data appear to be the results of experimental tests rather then device qualification tests, since the test currents were 20, 30, and 40 amperes. The aggregrate data from these experiments shows failure rates at 20, 30 and 40 amperes of approximately 5%, 22% and 36%, respectively. In other continuing tests at 20, 25 and 40 amperes, UL states that although approved devices have failed at 40 amperes, no failures have occurred at 20 and 25 amperes in over 2000 cycles. In a few limited tests failures have occurred at these lower currents when the wire nuts were deliberately mis-applied to improper wire sizes.

SUMMARY OF ALUMINUM WIRING RESEARCH AT BATTELLE INSTITUTE

1. ORIGIN, PURPOSE AND SCOPE OF STUDY

In June 1971, a research program on connections for aluminum wire and cable was initiated at the Battelle Institute in Columbus, Ohio. Support for the program was obtained from a number of U.S. and foreign companies including aluminum wire and cable manufacturers, wiring device and connector manufacturers and other manufacturers and users of electrical equipment which may be used with aluminum wire.

The purpose of the study has been to define the failure mechanisms and to conduct a reliability analysis of aluminum terminations.

The scope of the program includes solid and multistrand aluminum conductors ranging from circuit sizes down to communications-size wire. Termination types included in the study are crimp, clamp, binding head screw and set screw.

2. CYCLIC PERFORMANCE TESTS

Battelle has utilized a power cycle test to study the performance of electrical components. The test consists of passing currents of 40 or 53 amperes (depending on the wire size) through wired devices in cycles of 12 minutes ON and 6 minutes OFF. The device temperature, as measured by a thermocouple installed on the break-off tab, is monitored during the test. The connector devices are installed in open air during the tests and a torque of 6 in-lb is used. The criterion for failure is based upon an increase in the device temperature. Based upon laboratory studies, Battelle believes that a 10°C rise in device temperature is sufficient indication that substantial overheating is imminent. Therefore, a 10°C rise in temperature is used as the criterion for failure.

Most of the Battelle cyclic test data has been obtained using one type of receptacle and they question the reliability of extrapolating the data to other devices.

3. CHEMICAL AND MECHANICAL PROPERTIES OF ALUMINUM ALLOYS

Numerous alloys of aluminum have been studied in the program including both "old" and "new" technology wire. The alloys were analyzed for chemical composition using optical emission spectroscopy and for various mechanical properties such as ultimate tensile strength, yield strength, elongation, elastic modulus, thermal stability, tensile creep and stress relaxation.

An attempt was made to correlate tensile creep and stress relaxation results. It was found that correlations between these results were poor. Battelle found that the optimum wire properties with respect to low stress relaxation are 1) low tensile creep, 2) small stress dependency for creep, and 3) as low a yield stress as practical.

Battelle reports that, for "old" technology wire, stress relaxation at room temperature can result in substantial loss of metal-to-metal contact between the wire and the screw or connector plate in a relatively short time. However, for "new" technology materials, there is no viable mechanism based on stress relaxation to account for substantial screw loosening. They also report that no correlation has been found between any measurable mechanical property and termination performance.

4. EFFECT OF SCREW MATERIAL AND TORQUE ON FAILURE RATE

Studies were conducted with steel, brass and aluminum binding head screws with various metallic platings. Zinc was not recommended as a plating material because of its susceptibility to oxidation and its general metallurgical incompatibility with aluminum. It was also found that the screw material may have the greatest influence on the termination reliability. The termination failure rates were lowest with aluminum screws and highest with steel screws.

The studies have shown that increasing the torque of the binding head screw does not improve the initial contact resistance significantly, however, it can increase the life expectancy substantially.

5. FAILURE MECHANISM

The studies to date have led Battelle to conclude that microscopically small motion occurring at the termination point is the prime factor in leading to overheated terminals. The same mechanisms are thought to apply to both copper and aluminum wire although they can and do occur at different rates. As a result of the motion, a wear or fretting process occurs which gradually destroys the metal to metal contact by the formation of an oxide film at the interface. The oxide is a path of high resistance and results in overheating at the interface. The motion presumably can be due to thermal expansion and contraction although Battelle does not specifically say this.

In distinguishing between copper and aluminum wire, Battelle believes that aluminum is less forgiving of motion than copper and that a higher force must be maintained in an aluminum wired system to prevent motion or to escape the consequences of it. The studies show that if motion occurs, failure will occur in the following order: bare aluminum first, nickel plated aluminum second and copper or copper-clad aluminum third.

Battelle believes that connector devices designed to prevent motion would substantially reduce the possibility of failed (overheated) terminations.

6. PREDICTION OF LONG-TERM PERFORMANCE

Battelle has applied the Arrhenius time-temperature equation to predict the long-term performance of connectors from short-term test results. Basically, the process involves determining the <u>rate</u> of degradation at several elevated temperatures and extrapolating the rate curve to the desired (lower) service temperature. The rate of degradation is greater at elevated temperature than at the service temperature so that, presumably, long-term performance can be predicted in a much shorter time than would be required at the service temperature. By applying the Arrhenius relationship to the results of power cycle tests, Battelle has predicted lifetimes for various wire alloys and other components.

The reports emphasize, however, that the Arrhenius analyses do not include factors such as loose screw connections, wire disturbance or motion which could accelerate the degradation substantially.

The studies show that the failure rate is extremely sensitive to temperature and that the ambient air temperature may have a very significant effect on the test results. Battelle believes that testing specifications should be based on the temperature of a standard control device rather than on current because of the rate dependence on temperature.

7. INDIUM PLATING

Conventional connector devices were modified by plating with indium. The indium platings varied in thickness from 0.2 mil to 1.0 mil. Both side wire and push wire devices were plated.

With the indium plated side wire device, excellent temperature stability was achieved at 40 to 50 ampere testing. At 50 amperes, 20°C temperature rise failures were observed, but thermal runaway conditions were not reached within 2000 cycles. Typically, a 20°C rise in temperature was followed by a sharp drop in the terminal temperature followed by a longer term stability or a later transient rise.

A push wire receptacle, which in previous experiments would not function reliably with any available aluminum alloy, was modified with 0.2 and 1.0 mils of indium. During 1000 cycles, the push wire device exhibited stable performance within a 10°C temperature rise limit.

Thus, the indium plating was shown in these preliminary experiments to increase the performance of the devices by preventing thermal runaway.

Battelle reports, however, that indium diffuses with other metals such as copper. The diffusion process changes the characteristics of the indium but it is not yet known if the diffusion is deleterious to the connector performance.

8. PUSH-WIRE DEVICES

Battelle studies have shown that push-wire devices perform poorly with bare aluminum wire.

9. WIRE-NUTS

Battelle has studied two typical wire-nut devices using two wire (Al-Al), two wire (Al-Cu), and three wire (Al-Cu-Al). The wire size was No. 12 AWG. The results have shown that the highest failure rates were obtained with the Al-Al, two wire connection when tested at 40 amperes. The Al-Cu two wire connection yielded the lowest failure rate of the wire-nut connections tested.

The results indicate that the wire composition is a major factor in determining pigtail reliability. Battelle believes that the nature of the surface film on the wire is the dominant factor in leading to failure.

The tests that have been conducted show that only one type of aluminum wire with wire-nuts has been able to survive the same type of cyclic test required for other parts of the electrical system. This aluminum wire has been shown to have a surface coating of MgO.

Battelle also conducted studies in which the steel springs of wire-nuts were plated with indium. The results indicated a definite improvement in the performance of one type of wire-nut. But the degree of improvement was not sufficient for reliable performance of more than one and possibly two additional aluminum alloys.

10. CO/ALR DEVICE

Preliminary tests with a commercially available CO/ALR device without indium plating and No. 10 EC aluminum wire at 6 in-lb torque have shown that a device temperature increase of 20°C can be obtained in less than 700 cycles if the Battelle wire disturbance is used. However, Battelle expresses concern that the wire disturbance test may be too stringent because old style devices with #12 copper wire at 6 in-lb also fail the test after one or two disturbances. Since a significant field failure rate with copper wired old style devices has not been identified, the wire disturbance test may not actually represent field conditions.

11. JOINT COMPOUNDS

Battelle has studied two joint compounds which are supposed to help reduce the termination problems with aluminum. The system chosen for evaluation was a worst case condition using a conventional device, EC-H 19 (high stress relaxation) wire with distorted loops, 6 in-lbs torque and 40 amperes.

The results showed that neither joint compound improved the initial quality of the connection or improved operating characteristics.

12. CATEGORIES OF FAILURE DISTRIBUTIONS

Battelle believes there are two categories of failure distributions with aluminum wired devices. The first category includes devices failing in a relatively short time after installation. The major factor contributing to these failures is poor workmanship. The second category of failures are those which occur much later due to slow changes that occur with time.

13. TRANSIENT LOADS

Recently, Battelle has started a study with high transient loads (90 amperes) using electric lamps. There is preliminary evidence of greater degradation with the transient loads than with resistive loads. The device temperature with both transient and resistive loads starts at about 39°C. However, after about 15 days the temperature of devices using transient loads increases to 50-55°C whereas devices with resistive loads remain temperature stable for months.

NICKEL PLATED ALUMINUM
FOR ELECTRICAL WIRING

A Swedish company, Sieverts Kabelverk, has developed a nickel plated aluminum wire for use in electrical applications. The commercial name for the product is SINIPAL. Sieverts Kabelverk maintains that the use of SINIPAL averts the termination problems observed with bare aluminum wire.

The wire is made by electroplating a layer of nickel, about 1.5-3.0 um thick, onto bare aluminum wire. According to the manufacturer's literature, nickel was selected as a plating material over other conductive metals because:

1. nickel requires the lowest contact pressure to conduct current
2. nickel oxide forms at the slowest rate
3. nickel forms the hardest surface.

Laboratory tests have been performed in Sweden to compare the performance of bare aluminum, copper and SINIPAL with various connectors. These tests have shown that SINIPAL wire connections operate at temperatures and contact resistances that are comparable to those obtained with copper connections. The results of field installations also indicate that SINIPAL can be used to form reliable electrical terminations.

Information obtained from the Swedish Electrical Commission indicates that all electrical devices to be used in Sweden will be nickel plated to assure maximum reliability.

Based on the experience to date, Sweden is considering the adoption of a national standard for the design and testing of PVC insulated wires. The standard will include SINIPAL.

Literature Survey

Screw Termination of Aluminum Wire

Aluminum wire has been used for many years as an electrical conductor in many different applications. This paper is a very brief summary of the technical information pertaining to the termination of aluminum wiring used in homes. There are many different methods to terminate aluminum wire -- welding, soldering, crimping, bolting, etc.; this paper is concerned primarily with screw terminal terminations as used in branch circuit wiring in residences.

In order to better understand the problems of terminating aluminum wire, a brief summary of the properties of aluminum wire and, for comparison, the properties of copper wire is necessary.

PROPERTIES OF ALUMINUM WIRE

The aluminum wire used for conductor applications has a content of greater than 99 percent aluminum; the remainder of the wire is composed of different combinations of iron, copper, silicon, and magnesium. By varying the combinations of these elements and by controlling the production processes it is possible to produce wire having different tensile strengths, creep strengths, ductilities, hardnesses, etc. At present there are a large number of different alloy wires, each having different particular properties.

Table 1, lists the typical properties of aluminum and copper wire. As shown by the table, the two materials differ widely in almost all properties.

Aluminum wire has 62 percent of the volume conductivity of copper wire. Hence for an equivalent voltage drop in the wiring system it is necessary to use larger wire when using aluminum wiring for a residential branch circuit. For a twenty ampere circuit number 10 wire is required; for a fifteen ampere circuit number 12 wire is required. If copper wire is used the wire would be two sizes smaller, #12 wire for twenty ampere circuits and #14 wire for fifteen ampere circuits. When using aluminum wiring, the wires are physically larger and with some alloys, stiffer than the equivalent copper wiring. What effects this may have on the workmanship -- how well the electrician installs the wiring -- has not been well determined. Field reports and laboratory data on the reliability of aluminum terminations indicates that workmanship is very important in determining the performance of the terminations.

OXIDE FILMS

When exposed to air, aluminum rapidly (less than seconds) forms an oxide film that; is difficult to remove, is nonconductive and is mechanically strong. The oxides of copper, in comparison, form slowly, are easily removed, and are semiconductive. It is this difference in oxide formation and its properties that determines many of the differences in the problems of terminating aluminum and copper wires.

Most of the oxide formed in air on an aluminum wire is a hard barrier type; it forms rapidly and will reach thicknesses of three to ten nanometres depending essentially upon the temperature of the wire.[2,3,6] This film is, for all practical purposes, an insulator and must be removed or displaced before a satisfactory termination can be made. Conduction through the oxide film by an electron tunneling process is possible, however, the resistance of the termination would be such that the termination would reach excessive temperatures with the currents used in household circuits.

In order to obtain a low resistance termination the oxide film must be displaced or fractured and a metal to metal contact established. Since the film is very thin, brittle, and harder than the aluminum, sufficient pressure applied to the wire will cause the film to break like thin ice over mud. Sufficient pressure will cause the comparatively soft aluminum to ooze through the cracks in the oxide film. In a screw termination this aluminum oozing through the oxide film will make a metal to metal contact to the back plate of the outlet. However, this contact may not be sufficiently stable for a termination. The broken oxide pieces on the surface of the wire create asperities at the contact interface which are harder than the aluminum. These asperities will limit the number of metallic contacts which will be formed for a given pressure between the wire and the back plate (this pressure is largely determined by the torque applied to the screw of the outlet). These metallic contacts may be lost due to mechanical motion of the termination; movement may cause the aluminum at the contacts to oxidize since the asperities may prevent a complete seal around the metallic contacts.

In a screw termination a low resistance contact is made between the wire and the head of the screw; the head of the screw plows a path through the surface of the wire removing the oxide film and forming metal to metal contacts to the aluminum.

Our data agrees with the above description of the contact interfaces. Measurements show that the resistance of the contact between the wire and the backplate is high at low screw torques. The resistance decreases as the torque on the screw increases but is higher than the resistance between the wire and the head of the screw. At six inch-pounds torque on the screw, most of the current passes from the wire to the screw head to the back plate; typically less than one-sixth of the current passes from the wire directly to the backplate. At six inch-pounds torque, the resistance from the wire to the back plate varies considerably from outlet to outlet; after current cycling the termination, this resistance increases rapidly and appears to be unstable. On tests of devices used before the new devices were developed, this current path from wire to backplate is unreliable and is unsatisfactory as a termination for lower torques applied to the screw of the device.

CREEP

In order to maintain a stable and satisfactory metal to metal contact that has been made by breaking through or removing the oxide film it is necessary to prevent relative motions at the contact interface. In a screw termination these relative motions will be small if the stresses applied to the wire by the screw are retained. It is for this reason that the creep of the wire in the termination is believed to be important. Creep can be defined as the time dependent deformation of a material when a stress is applied at particular temperature - the time dependent part of strain resulting from a stress. In a screw termination the stress is applied to the wire by the torque on the screw. The aluminum wire will tend to creep under the screw head or cold flow away from the stressed area. The amount of the creep or cold flow is dependent upon the alloy of the wire, the stress, the temperature of the termination, and the time for which the stress is applied. Creep rates for different aluminum alloys used as conductors may vary by a factor of fifty so it is difficult to compare the creep rates of aluminum to those of copper.[2,4,5] In general, under equivalent conditions, the creep rate of aluminum wire is greater than that of copper.

STRESS RELAXATION

Another factor that is important to an aluminum termination since it affects the stress retained in a termination is the stress relaxation of the wire. Stress relaxation is the time dependent change in stress not accompanied by a dimensional change or strain. The stress relaxation of a wire is dependent upon the alloy, the applied stress, the time at stress, and the temperature. Some alloys of aluminum have stress relaxations that are lower than copper and some alloys have stress relaxations that are higher.[4]

In a screw termination it is difficult to separate the effects of creep and stress relaxation - they both tend to lower the stress applied to the wire by the screw. Abbott, Battelle Columbus Laboratories,[2] measured the total stress relaxation in a screw termination for several different alloys of wire. His data indicated that after 10^6 minutes some alloys retained approximately 90 percent of the stress, other alloys retained approximately 35 percent of the stress. In his experiments the stress was applied by torqueing the screw of the terminal to 14 inch-pounds.

THERMAL EXPANSION

A mechanism that may reduce the stress applied to the wire by the screw in a screw termination is due to the differential expansions that take place when the termination is thermally cycled. In many of the old devices the wire was aluminum, the screw was steel, and the backplate was brass. The coefficient of expansion for aluminum is twice that of steel; for a given temperature rise the aluminum will expand more than the steel screw, this increases the stress on the aluminum. If this increased stress exceeds the yield strength of the aluminum wire the wire will be permanently deformed. When the termination returns to lower temperatures, the stress on the wire will be less than the stress prior to the thermal cycle. If the screw is made of brass the decrease in the stress for a given thermal cycle should be less since the coefficient of expansion of brass is closer to aluminum than that of steel. It has been noted that devices with brass screws have lower failure rates than the same devices having steel screws. Whether this difference in failure rates is due to the effects of differential expansion is not known at this time.

INDIUM PLATED CONTACTS

Data indicates that the use of indium plating at the contact interfaces has resulted in marked improvements in the performance of aluminum wire terminations.[2,3] Indium at the interface of the contacts reduces the electrical resistance and improves the mechanical stability of the termination. Contact resistance measurements and micrographic observations were made on crossed aluminum and plated aluminum wires to investigate the effects of compressive force and relative motion on the contact.[3] These tests indicated that indium-aluminum contacts were superior to contacts of aluminum to aluminum or, to any other plating, both with respect to the resistance level and the mechanical stability. Indium is able to flow under pressure into the microscopic cracks in the oxide film and because of its adherence properties, it can retain good contacts despite tensile stress disturbances or stress relaxation of the termination. However, the indium plating used in a contact is subject to degradation due to interdiffusion and alloying of the indium with copper-based materials.[9]

The good contact performance of indium plated contact-interfaces is due to the mechanical properties of indium; its extreme softness and ductility, its ability to adhere to other surfaces and its ability to form a gas-tight seal around asperities. The formation of intermetallic compounds by interdiffusion and alloying will alter the mechanical properties of the indium at the interface which may lead to a degradation of the performance of the termination. The rate of the alloy formation has shown to be comparatively fast, converting 5x10 -3 millimetres of indium plating to an alloy in five years at room temperature; at 100°C, the same indium would converted in approximately 1000 hours.[9] It has been determined that a blocking layer of nickel plating between the indium and the copper-based materials will effectively prevent the alloying of the indium for long periods of time. If the contact is first plated with nickel and then plated with indium, it will take more than forty years for the complete alloying of the indium rather than the 1000 hours when the nickel plating is omitted.

SCREW TERMINAL TERMINATIONS

In order to make a low-resistance, stable, termination that will be effective for many years, it is necessary to consider those properties of the aluminum conductors just discussed. To obtain a low-resistance contact the oxide film must be removed or broken and a metal to metal contact established. To obtain stability and long life this metal to metal contact must remain as undisturbed as possible; the compressive forces exerted on the wire by the screw must be retained, relative motion between the wire, the screw, and the backplate must be minimized, and corrosion at the contact interface must be prevented. However, creep, stress relaxation, plastic deformation due to differential expansion, and chemical activity (all properties of aluminum wire) tend to disturb the contact interface, possibly endangering the established metal to metal contacts and lowering the performance of the termination. It is difficult to qualitatively determine the effects of these properties on the performance of a screw termination. A screw termination, though physically simple, is mechanically complex. It is difficult to determine the actual stresses, strains, interface areas, thermal expansions, etc., in an actual termination. For this reason, the Underwriters Laboratories established performance tests of the devices and conductors that are used in terminations rather than a set of specifications for the devices and conductors.

In 1971, Underwriters Laboratories established a set of performance requirements for both the conductors and the devices that will be used in residential wiring; these requirements are discussed in detail in another section of this report.

In order to meet these performance requirements the manufacturers of aluminum wire developed new alloys for the conductors. Generally, these new conductors have lower creep rates, lower stress relaxation, better ductility, and better thermal stability than the conductors previously used for wiring.

It is difficult to assess how effective these new conductors will be in improving the performance of screw terminations, because at the same time, manufacturers of devices took steps to improve their devices in order to pass Underwriters Laboratories performance requirements.

Generally, the new devices have the following improvements; brass screws with larger heads rather than steel screws, serrated backplates rather than smooth backplates, improved wire restraints, and indium plated backplates and screws rather than plain, brass backplates and zinc plated screws (one manufacturer does not use indium plating but lubricated the screws to obtain a greater force on the wire for a given torque.)

According to laboratory tests, the new devices perform much better than the old devices. At the present time, the original devices sent to Underwriters Laboratories for performance tests and approval, are still under the tests. These devices have shown no degradation or failure though they are connected to conductors considered poor for terminations.

These devices do not have a barrier material-nickel plate-between the indium and the brass backplate. At this time, it is not known what the effects of the alloying of the indium plating will have on the performance of the device terminations. The devices under tests at Underwriters Laboratories were connected to the conductors before alloying of the indium took place. Since the devices have been on tests at elevated temperatures for the past three years it is believed that the indium plating may be completely alloyed. No noticeable change in the performance of the devices has been observed.

It is believed that if the indium plating has been completely alloyed before the device is connected to the conductor, some degradation in the performance of the termination is possible. This problem could be solved by using a barrier material such as nickel; the improved performance of the indium plating would be possible for the expected life of the device, perhaps fifty years.

Symbol	Al	Cu
Atomic Weight	26.98	63.54
Density	2.70	8.89
Melting Point °C	660	1083
Specific Heat	.226	.092
Coefficient of Linear Thermal Expansion (microin/m/C)	23.6	16.5
Thermal Conductivity (20C° Cal/Sq. cm/cm/sec/C°)	.53	.941
Electrical Resistivity (20°C micro-ohm/cm)	2.8	1.7
Electrical Conductivity (% IACS) (Equal Volume)	62·	101
Electrical Conductivity (Equal Weight)	204	100
Current Carrying Capacity	80	100
Modulus of Elasticity	10	17
Tensile Strength (Annealed) (10^3 psi)	12	38
Yield Strength (10^3 psi)	4	10
Hardness (Brinell)	50	103
Solution Potential (1N NaCl 3% H_2O_3 N/10 Calomel Scale)	.85	.20

TABLE 1 TYPICAL PROPERTIES OF ALUMINUM AND COPPER

From: Lemke, Timothy, "Terminating Aluminum Conductors-State of the Art", Insulation, (September 1968)

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NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 75-723	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Aluminum Branch Circuit Wiring in Residences
Summary Report for the Consumer Product Safety Commission
January - September 1974

5. Publication Date: June 1975

6. Performing Organization Code

7. AUTHOR(S)

Staff of the Institute for Applied Technology - NBS

8. Performing Organ. Report No. NBSIR 75-723

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No. 4401412

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Consumer Product Safety Commission
Washington, D. C. 20207

13. Type of Report & Period Covered: Summary Report

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

A companion report reviewing the history of the use of aluminum in residential wiring and evaluating existing field data is available. This report is NBSIR 75-677 entitled "Hazard Assessment of Aluminum Electrical Wiring in Residential Use."

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.)*

This report is a compendium of information on aluminum wiring in residences, originally prepared for the Consumer Product Safety Commission. It contains a summary of experimental research carried on at the NBS laboratories on the problems of terminating aluminum wires to screw connections as well as other pressure connectors. Since this report is an overview of the technical aspects of the aluminum wiring problem, it also contains a review by NBS staff members of available material furnished by Underwriters Laboratories and Battelle Institute. Both of these institutions are major contributors to this particular field of information.

The report also includes abstracts by NBS staff of some four volumes of testimony taken at public hearings at Washington, D. C. and Los Angeles, California during the spring of 1974. Additional information on the pertinent physical properties of aluminum, information on failure mechanisms, possible corrective actions, connector cycling tests, etc., is given in a brief literature survey and two relevant memoranda on the subject. The report concludes with a fairly extensive bibliography.

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, Consumer product safety, Current cycle testing, Electrical connection failure, Electrical receptacles, Residential wiring

18. AVAILABILITY [X] Unlimited

[ ] For Official Distribution. Do Not Release to NTIS

[ ] Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13

[X] Order From National Technical Information Service (NTIS) Springfield, Virginia 22151

19. SECURITY CLASS (THIS REPORT): UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE): UNCLASSIFIED

21. NO. OF PAGES: 91

22. Price: $4.75