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Some Thoughts on Electrical Connections

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ABSTRACT

This report is a subjective and personal statement of my experiences and thoughts regarding electrical connections, in general, and aluminum wiring for homes, in particular. It is not a statement of official position of the National Bureau of Standards (NBS). It is entirely possible that other members of the NBS staff may not agree with many statements made in this report. It is based on some considerable experience and where the ideas expressed are not based on such experience, I hope this is clearly indicated.

My conclusions are that present day technology of electrical distribution wiring in residences is not in keeping with good engineering practices available today. This is true relative to both copper and aluminum wiring.

Key Words: Aluminum wiring; Electrical connections; Pressure terminals; Wire creep

Introduction

Sometime after Dr. Stanley Warshaw joined NBS as Director of the Center for Consumer Product Technology, he asked me to write out my thoughts on electrical connections, in general, and aluminum wiring, in particular. This report is the result. Because many of the ideas in this paper are based only on my own experiences and my prejudices, the report should not be considered an official statement of NBS on aluminum wiring or, for that matter, on anything else in this paper.

When we did the original work at NBS for the Consumer Product Safety Commission, we were rather anxious to expand the work and to investigate the chemistry and physics of connections as a general, broad problem, at least as it affects electrical branch wiring. However, the tasks which we were requested to address were rather specific and limited in scope, and we were unable at that time to get the support necessary to do the work as extensively as we would have liked. It is for this reason that many of my comments in this report are based either on prior experience outside of NBS or are based on judgments resulting from rather meager tests.

I would like, first, to state my qualifications for writing this. While I was getting my two electrical engineering degrees and until I came to NBS in 1938, I worked as an electrician and as a radio mechanic. One company for which I worked for several years built electrical fixtures and also sold and installed them. I also did a great deal of radio service work and a considerable amount of custom building of various radio equipments. During the war, at NBS, I was involved with proximity fuses, guided missiles, and so on. It was for one of these fuses that printed circuits were invented in the United States. In connection with this work, I was exposed to many difficult problems in electrical connections.

From 1954 to 1964, I headed my own company where about half of our effort was devoted to work for the Sprague Electric Company, a major maker of capacitors. This has a direct bearing on what I am going to say because capacitors are usually made of aluminum foil and connections to this aluminum foil are made by soldering, crimping, riveting, etc. My staff and I designed and built equipment for automatic soldering, automatic winding, and other associated processes in making capacitors. During this period, I also worked on a great many machines for others, including radar, Post Office letter-sorting machines and computer equipment.

In 1964, my company joined Control Data Corporation and I was in charge of their OCR Laboratory. Here I learned that the quality of wiring in computers is quite different from almost anything else that I have worked on except, possibly, ordnance. A service call caused by the failure of a relatively simple part of a computer may cost several hundred dollars. We therefore asked our workers to make all connections very carefully because the cost of the connectors and connections is a small fraction of the total cost of a computer, its operations and its maintenance.

Types of Electrical Connections

The literature describing electrical connections is very extensive. There are books, technical articles and, of course, thousands of patents on devices that have to do with electrical connections. This report is by no means an attempt to cover the whole field. Its primary purpose is to discuss the types of electrical connections that one fashions with unsophisticated tools and, particularly, for home wiring or for things with which we are familiar in consumer goods, such as lamps or small appliances.

Electrical connections, for the purpose of this report, can be classed into two basic types. One is where the metal is continuous; that is, the connection is made either by some form of weld between the parts to be connected or by solder. In the other class, the connection is made mechanically; that is, by pressure between two or more conductors that have to be connected.

Welded Connections

Welded connections can be, again, of many types. A common type would be when one welds two parts by the application of external heat. I have been told that the Russians use aluminum wire for home and for industrial wiring and that they weld the wires to the terminals with thermite. This is not a cheap and easy method; it is dangerous; and if one considers the fire hazard and the pressure of time under which our people work, it does not appear to be a very attractive system. The same can be said of welding using torches, electric arcs, and so on. Spot welding is often used but not for home wiring. Spot welding is commonly employed in factories when connecting wires to terminals and when attaching contact points to various parts of machinery, such as in circuit breakers. This type of welding is done by passing a large amount of current for a very short time through the connection. This welds the terminal to the back material because of the relatively high electrical resistance between the two parts. The connection can be inspected either by mechanical means (trying to separate the parts) or by measuring the electrical resistance of the weld or, very often, simply by the sound that occurs when the connection is made. The machine that spot welds makes a distinctive sound during the weld and an experienced operator can easily tell whether the connection was well made. There is no doubt that spot welding is an excellent and high-speed method of making electrical connections but there is also very little doubt that it is completely unsuitable for electrical wiring in a building - certainly not in the usual type of construction.

Soldering

Another and widely used method of electrical connections, of course, is the soldering together of two or more elements by a low temperature metal, such as a tin-lead alloy or a tin-zinc alloy. For this purpose, the usual procedure is to heat the metals to be joined and to coat them with a flux which reduces the oxide coating and then to "wet" the pieces by the melted solder. When the joint cools, the whole assembly is electrically conductive and this technique is very widely used. This method is especially good for copper, particularly tinned copper. It is more difficult to use with steel because the oxide is more difficult to control, and it is very difficult to apply to stainless steel and aluminum. For these metals, special fluxes have to be used and the technique has to be different.

One of the problems in using solder is the removal of the flux when the joint is finished. Many of the fluxes are corrosive; even those which are less corrosive still absorb moisture, and to obtain a good, permanent joint cleaning is most important. The requirements for using heat and for subsequent cleaning make these techniques not particularly well suited for electrical wiring in buildings. Power is not always available, particularly because it may be shut off just in those very areas where the connections are to be made. Proper cleaning after soldering is extremely difficult where the connection is in a wall structure. Compare this, for example, to work done in a factory on printed circuit boards: these boards can be easily run through special machines both for soldering and for cleaning.

At this point it should be noted that a great many soldered joints are used in the manufacture of electrical capacitors where the aluminum foil is soldered to copper leads by means of special solders. These solders are approximately half zinc and half tin and are used without flux. The procedure is to rub the parts together in such a way as to "work" the solder into the aluminum, essentially abrading the aluminum oxide mechanically. The system works very well and billions of such capacitors have been manufactured and are in use.

It is possible to tin plate aluminum, using conventional resin-core solder by a technique which is more suitable for demonstration purposes rather than as a practical matter. The technique is to take a relatively large soldering iron and deposit a large glob of solder and resin flux over the tip, which is in contact with the aluminum sheet. By rubbing the soldering iron over a small area of the aluminum sheet, the oxide can be broken while further oxidation is prevented by the flux and solder that surrounds the tip. One eventually finds that the solder adheres to the aluminum and does not move when the iron is moved. If at this point the iron is removed and the solder is wiped off, one finds a spot of aluminum covered with tin to which wires or other objects can now be soldered conventionally. This technique requires a relatively large area of material to be covered, a very large amount of solder and flux compared to the joint itself, a horizontal position of the aluminum and, in general, is not suited for application to electrical wiring in a building.

Pressure Connections

A connection made between two metals by mechanical pressure is perhaps the most widely used type of electrical connection today. These may be of many basic types. They may be temporary connections, such as the plug and socket used for electrical cords, or electrical components plugged into special sockets, such as printed circuit boards and digital circuitry plugged into special sockets, millions of vacuum tubes still plugged in and working in sockets of millions of radio receivers and, particularly, aluminum or brass connections used at the base of electric bulbs. In this case, the bulb is screwed into a socket; modern bulbs usually have aluminum bases with solder tips and they fit into sockets which are of aluminum or brass. The contacts are reasonably satisfactory except in some special atmospheres. The number of such connections runs into the billions.

Another type of commonly used temporary connections is, for example, the contacts of a circuit breaker. These connections are spring loaded and vary in size from tiny things used for 15 amp circuits to tremendous contacts used in large circuit breakers in power plants.

Where special requirements have to be met for contacts that either have to carry current at right angle to the contact or which have to break large currents, metal contacts are not very satisfactory and graphite compositions are used. Examples are brushes of motors, sliding contacts in variable voltage transformers (these are sometimes used in homes for light dimmers), contacts of large circuit breakers, and so on. The advantage of the higher resistance of the contact material is that it prevents circulating currents when more than one turn of a transformer or commutator segments are shorted. Such contacts are also good in situations where the contacts have to withstand arcing because the material prevents the welding of contacts. Very often, in critical applications, precious metals are used, such as gold and silver and particularly platinum and related metals, the latter because of the high temperature required to weld them. These contacts, of course, are expensive and are used only where the expense is justified.

A type of pressure connection that is used a great deal is the connection between the heavy conductors and the terminals of lead acid batteries used in our automobiles. Again, there are hundreds of millions of these contacts. The lead would not normally be considered a good metal for pressure connections because of its tendency to flow but the contacts are very heavy, and considering the fact that the starting current of an automobile may be of several hundred amperes and that the voltage available is low, it is a high compliment to the lead connection that it works as well as it does. In some of such contacts, steel springs are embedded in a lead terminal so as to provide the pressure while the lead itself makes the connection.

The use of steel springs to provide pressure while the current is carried by another metal has been used in other devices, particularly in many high quality sockets for vacuum tubes manufactured many years ago. Here, a U-shaped steel spring pressed together the copper strip that made the connection to the pins of the vacuum tube. The idea of using steel springs, even in simple devices to provide forces for connections, goes back at least 50 years. I think it is a pity that such steel-backed brass terminals are not generally used in outlets for plug-in devices in homes.

Coming closer to the subject of this report, there are the wire connections that are most commonly used in outlets and switches found in our walls, floors and ceilings. Here a wire is put under a screw and the screw head presses the wire against some type of metal plate. These screws are generally tightened by a conventional screwdriver and this works very well for copper wires but less satisfactorily for aluminum. In recent years, it has become quite customary not to use a screw connection, but simply push a wire into a hole in the device where the wire is caught between a metal plate and a spring finger formed out of the metal of the terminal. The edge of the spring cuts into the surface of the wire and serves both to make the electrical connection and to prevent the withdrawal of the wire unless the spring is pushed aside by a tool.

I do not like this "backwired-type" of connection because the area of contact between the wire and the connector is very small and the lug must remain springy since nothing else holds the connection together. Now, if the device ever gets hot because of a poor pin plug that does not fit the socket well, or for whatever external reasons quite aside from the heat due to the connection itself, the brass loses its springiness, the wire becomes loose, and an overheated connection results. The backwire device is cheap and easy to use, but I think one could design an equally simple and inexpensive connection with a screw which would work with either copper or aluminum.

When I worked as a consultant for Cutler/Hammer, this company used aluminum ribbons approximately two inches wide for winding the electromagnetic coils for very large lifting magnets. Here the connection was made by swaging lugs out of the ribbon into sheets of other material which were then connected to the outside leads. A great many extruded terminals over a very large contact area were pressed together very firmly so as to break the oxide and provide a tight joint. The reliability of these connections had to be very high because it is very highly undesirable for a lifting magnet to drop its load.

Another popular connection which depends on mechanical pressure is the wire-wrap connection. Here a rectangular or square terminal is used and the copper wire, which may be bare copper or tinned-copper, is wrapped tightly around this post, the number of turns being something of the order of five to ten. This method was invented at the Bell Laboratories and is used widely in the telephone systems and in computer construction. It is a much better connection than one would guess at first glance. The twisting of a wire over a small diameter, rectangular terminal "works" the wire rather severely and produces great pressure at the corners. While examining the development of this connection at Bell Labs many years ago, I was shown such connections immersed in acid where most of the wires were eaten away but the connections were still good because the wires were in such close contact at the corners that the acid could not attack the metal at the joints. This type of connection is relatively easy to make as there are no loose pieces of wire to get rid of, it requires no solder, is compact, and fast to make, but it is particularly suited to small diameter wires. I do not know whether it is possible to make this type of connection for the thickness of wires used in home or industrial electrical wiring.

A very popular device for connecting together two or more wire is the wire-nut. These twist terminals consist of a cone of spring wire, such as steel, which is surrounded by some insulating protector. The electrical wires to be connected are fed into the cone and the cone is turned. This does two things. It usually twists the wires together and the spring wire cuts into the surfaces of the electrical wires, pressing them together and thus forming an electrical connection between them. It is not known at the present writing whether most of the current flows between the wires themselves or through sections of the spring. This is something that we hope to find out in the near future. It is also of interest to us how such connections behave with copper wires as compared to how they behave with aluminum wire, or a combination of copper and aluminum. It is surprising that steel, which we were told many times should not be used with aluminum wire, is used extensively (almost universally) in wire nuts.

Wire nuts are used very widely; they are easy to use and certainly much easier to use than the type of electrical connection that was made when I was an electrician in the 1930's. We had to solder the leads together and cover them with rubber tape and, finally, cover the whole joint with friction tape (a rubberized cloth compound). The wire nuts are easy to use; they are satisfactory, at least for copper wires, are much less so for wires of aluminum, particularly where stranded copper is connected to solid aluminum. The use of wire nuts for aluminum wiring will be touched on again later in this report.

Wire nuts behave quite well in laboratory tests as long as one doesn't pass much more than the rated current through them. They almost always fail, and fail rather rapidly, under heavier current because they don't have much heat dissipation capacity, particularly because the connection itself is thermally insulated, and, even if the connection is proper, the wire and the spring get warm at currents, say, of 40 to 50 amperes. Many of the new wire nuts (that is, recently made wire nuts) have thermoplastic covers which melt rather easily. This means that a connection can short to the box or to other wires when such outside insulation melts away. Thermosetting material, such as bakelite, chars and emits a violent stench when it gets overheated. This indicates that something is wrong. At least in this respect, it is a better material but much more expensive than the thermoplastics which are used very widely today.

Another very widely used pressure connection is the so-called crimp connection. The wires that are to be connected together or to another device are fed into a metal tube and the metal tube and the wires are squeezed together. This type of mechanical joint has been used not only for electrical connections, but has been used as termination for flexible cable drives and for many other items. When the pressure is applied simultaneously from all directions, the metal is actually shrunk, the diameter of the outside tube is reduced, and if the connection is properly made so that the tube is not permitted to spring back, the connection is very good. The inside of the tube in a common terminal, such as made by the AMP Corporation, is made of metal which is serrated or perforated with small holes so that when such connections are made to a wire, the wire is squeezed or extruded into these small holes. This breaks the oxide and increases the area of contact greatly so that a very good bond is produced between the tube metal and the wire. In the AMP terminal, one side of the crimp connection is made re-entrant; that is, the tube curvature is turned inside out. This prevents the tube from springing back which, unfortunately, occurs with connections which are not as well designed.

One of the problems with crimp connections is that they must be made with proper tools and the closing distance of the dies must be controlled so as to squeeze the joint the correct amount. If too little squeeze is provided, the connection is not good enough because the wire is not deformed sufficiently and not squeezed into the perforations inside the tube. If, on the other hand, the wire is squeezed too hard, it can be cut and the connection can be destroyed. For these reasons, the tools that are used for crimp connections have carefully designed dies and require considerable pressure. In a factory environment, they are almost invariably power-driven, either pneumatically, hydraulically or by electrical motors, and the dies are designed for particular connectors and for a particular number of wires. In house wiring, these tools are difficult to use because they generally require power, are not convenient in crowded space, and there is a great danger that the improper tool would be used, producing an improper connection. There are hand-operated tools, but they are rather clumsy and difficult to use with only two hands.

A crimp connection is rather large as compared to, say, a screw terminal, and because the space in modern wall boxes is rather limited, such connections are usually covered by an insulating sleeve. These sleeves are applied loose and then shrunk by the application of heat. Again, this requires that heat must be available, which is not always convenient, and the unfortunate thing about the insulation cover is that it hides the connection, making inspection either very difficult or impossible.

Another problem with crimp tools is that they are quite expensive. Also, the changing of dies is not a trivial matter and it must be done correctly for changes in size of wire or type of connector. Such tools are particularly suitable for large-scale factory production where the same type of a connection is to be made over and over again. They are not as suitable for house wiring where the number of leads may vary and the size of wire may vary from terminal to terminal. A crimp tool is a particularly risky tool, as far as quality control is concerned, if it is used by inexperienced, untrained or lightly trained help with little supervision followed by poor inspection. There is the additional danger that, if the right tool is not available, an ordinary pair of pliers would be used to crimp such a connection with the result hidden by an insulating sleeve. This would be a worse connection than even that of the poorest screw terminal. When crimp connections are used in a factory, the wires are stripped by machines to exactly the right length and the machines are carefully adjusted to avoid nicking the wire. The lugs and crimp connections are supplied in labeled boxes and the workers do the same task over and over again, day after day. If they use the wrong lug, say, it soon shows up, the inspector notices it and the mistake is corrected; but these workers are not wiring terminals on a basement floor or in an attic; they are not pick-up people from the street who are induced by various means to be in a great hurry. In the high-quality wiring or devices for military use and computers, the workers are certainly not in a hurry; they are required to do a good job. Therefore, to say (as I have heard) that a crimp terminal is a good connection makes no sense unless the conditions are carefully specified. In fact, there are more wrong ways to use a crimp terminal than there are wrong ways of making a binding screw connection.

There is still another problem when crimp lugs are to be used with screw terminals. The new CO/ALR equipment has a provision for controlling the position of the wires. A small notch is provided in the insulation material of the outlet or switch through which the wire is to pass, preventing it from turning or loosening the screw. This particular notch interferes with the use of a crimp device if it is to be used under the screw head so that one would probably be forced to use pigtailing techniques: a short piece of copper wire can be connected to the aluminum wire by means of an interconnecting lug, then the copper wire placed under the head of the screw in the outlet or the switch. Such an arrangement requires more space in the box than a direct connection to the screw, besides being expensive. It certainly doesn't look like a proper approach except as a makeshift.

In discussing pressure connections of any type, it is particularly important to remember that the effect that keeps two or more bodies in tight contact, whether they are joined for electrical reasons or for mechanical reasons, is the fact that something is constantly pulling or pushing them together. This means that under normal conditions a spring force must be applied to the joint for as long as the bodies have to be pressed together. In an electrical connection, such as a screw type, for example, the force may come from the fact that the screw head is deformed, the screw itself is stretched, the plate under the wire is deformed, or the wire itself provides some spring force and, in fact, all of these elements combine to produce a tight connection. As long as the elastic forces remain in effect, the joint can be reasonably tight. If, for some reason, the elastic forces go to zero - that is, either the wire shrinks or the other members of the structure relax (that is, lose their spring tension), the joint becomes loose. This is a most important note for some of the things that will follow in this report.

This problem of maintaining pressure between bodies for electrical reasons has been recognized for a long time and the patent literature, among other data, is full of techniques for maintaining such pressures. Springs of various types are employed, for example, in power plants where connections between busbars must be kept tight. Belleville washers are probably the most common means to do this. Belleville washers are cone-shape washers which act as springs. They can easily be put under the head of a bolt or under the nut and when tightened are flattened and provide rather large forces. As far as I know, they are not used today in house wiring devices and I think that this is something that certainly should be looked into. I will have more to say about this when I get to the specifics of aluminum wiring.

The traditional method of connecting wires in home devices and in much electrical equipment today is to place the wire under the head of a screw or into a hole where the screw tip can be pressed against the wire. This last technique, using a set-screw, is common in many European fixtures and devices, providing a simple and a fast connection. Unfortunately, the wire is often cut by the screw, particularly when stranded wire is used. Hence, American technology tends to avoid this technique. (I know of no American device that uses such screw connections but I have seen a great many European devices that do.) American devices which are not wired in a factory generally use binder-head screws. The wire is wrapped around the screw and the head is brought down to hold the wire. Usually the screw does not fit into a nut but into a threaded hole in a brass plate. The brass plate may be extruded slightly before the thread is cut, providing more material for the threads. The female thread may contain no more than 1-1/2 to 2 threads. This leads to some difficulty which I will discuss later. Good workmanship requires that the wrapped wire not cross itself before the screw is tightened. The crossover tends to cut the wire and subsequent bending may break the wire at this point. If the screw is cocked by the crossover, it may jam the thread and, with aluminum wire, high pressure at that point may cause very high creep and the screw may later loosen. Heat is generated in the small area of such a joint. This is highly undesirable for aluminum wiring because oxide formation, expansion, contraction and many other problems are reduced if the temperature is kept at a constant and low value. For these reasons, crossover connections are not considered to be good practice.

Aluminum Wiring in Homes

Aluminum wiring was put on the market for wiring of residences without much fanfare and general discussion in the 1950's and 1960's. As far as

I know, there was no attempt to redesign the connectors from the types that were used for copper. This is in contrast to industrial connections which have been designed for the combination of elements that were to be connected. Conductors in power plants, high tension wires and lead-ins, and their connections have been designed for each other during, perhaps, three-quarters of a century.

Trouble developed when aluminum wire went into home use although it is very difficult to say that the troubles really were much greater than occurred with copper. The oral evidence that I have heard from many people in the Washington area and across the country suggests that aluminum gave more trouble, more over-heating, more flickering of lights, etc., but the data is not open and shut. Eventually, the connectors (that is, the equipment that was used with aluminum) were modified in response to complaints. An intermediate device marked "copper aluminum" lasted a short time; then the CO/ALR devices went into production.

The CO/ALR device differs from the earlier devices in that the screws are of brass and have larger heads; the wire fits into a groove under the screw head so that it is captured better; the plate on which the wire rests is serrated; many of the devices are indium plated; and the wire has some restraint so that when one pushes the whole device into a box in a wall, the twisting of the wires does not tend to turn the screws. It is my own personal opinion that these wire restraints are not good enough and that the wire should be captured by a positive restraint, not just a notch in the frame of the connector. It can easily slip out of such restraints, which results in undesirable torque on the screw. Fortunately, the serrations on the plate do lock the wire quite well and it is less likely that the screw will turn in the CO/ALR device - very much less likely than in the old-fashioned smooth-plate no-restraint contact.

At this point, let me review the characteristics of aluminum wire that make simple connections difficult. Aluminum creeps; it oxidizes readily; its oxide is a superb insulator; and the oxide is brittle. Aluminum is mechanically not as good as copper; it has to be thicker for the same current-carrying capacity; some alloys get cold-work rather easily and become brittle. However, it is a good electrical conductor and should be usable with suitable terminations. Historically, aluminum conductors have been used in industry for a long time.

In industry, aluminum has long been used for busbars in power plants where it costs less for given current requirements and also because of the greater stiffness for a given current-carrying capacity. This is important in case of short circuits. Busbar connections are made with heavy bolts; the aluminum is sometimes plated with other metals; the joints are periodically inspected and the bolts retightened. Belleville washers are usually used to maintain pressure in the joints as the aluminum creeps.

Aluminum has also been used for high tension wires for power transmission. Quite often the wires combine steel cords for coping with the mechanical stresses with aluminum to carry the current. Aluminum is also widely used for service leads into the home, and sometimes for heavy duty use even where the home is otherwise wired with copper.

Aluminum wire is used now extensively in winding motors and generators and has been used in squirrel cages of induction motors for a long time because of its special characteristics. When it is used in electrical motors as, for example, for hand-held drills, the connections are sometimes made by conductive epoxies, which usually consist of a binder loaded with a conductive material such as silver powder. This cement applied to the terminal makes a satisfactory connection in many applications, as in small power tools. The technique is simple, but it must be done correctly with the proper material applied in the right consistency; otherwise, the joint will not be conductive. It must be cured properly and must not spread beyond its intended site, for a running joint can cause trouble. This type of connection, too, is not a likely candidate for home wiring use.

It is obvious from the literature and the patent art that aluminum is certainly acceptable as a conductor, but industrial connections are more carefully made and with better tools by better workmen than are apt to be found when wiring residences. Industrial connections with thin wire are usually of the crimp type. The wire ends are carefully cleaned of their insulation and sometimes wire-brushed to remove as much oxide as possible. The wire is inserted into heavy duty connectors, which can either be bolted together or crimped by special power tools. Sometimes the wire is covered by grease with suspended metal powder in order to deter oxidation, then great pressure is applied to deform the aluminum. Any oxide present is broken during deformation, making for a good electrical connection. This doesn't always work well and service leads do occasionally give trouble in homes, requiring that the connections be redone. Depending on luck and workmanship, by and large the process works. It should also be realized that service entrance connections to homes are often via conduit or pipe, so that the danger of fire is relatively small. Home distribution panels are virtually always in steel boxes, as contrasted to the plastic boxes that are sometimes used in walls. The connections for heavy duty leads, such as lead-ins, are usually of the saddle type, where aluminum is not pressed under the screw heads, but is captured in a clamping device with a moving plate which, in turn, is driven by a large bolt. This can be driven by a wrench so that the connection squeezes the wire and deforms it under great pressure. The springiness of such connections helps to maintain the pressure. As I said, this type of connection doesn't always last but, generally speaking, is satisfactory.

Home wiring involves not only the lighter gauges, normally 14 or 12 for copper or 12 and 10 for aluminum, but also the heavier wires used for servicing air conditioners, electric heating systems, washing machines, etc. I have the impression that the heavier circuits have given as much trouble as the lighter; hence, any discussion of home wiring standards should cover these also.

Good copper connections are much easier to make. We know from extensive experience that an ordinary screw connection on copper, or a simple crimp connection, or a pressure lug, all work quite well. If the workmanship is even partly satisfactory, the connection is satisfactory, although not as satisfactory as commonly believed. Certainly copper joints are not trouble free, but a good copper connection can be made much more easily than a good aluminum connection.

Without going into the economics, we can note that the electrical outlets, switches, and other home items have to be inexpensive in manufacture and installation. In fact, installing a device is usually more expensive than its original cost. Military or computer applications often call for high quality connections which cost more than the equipment to be connected. A $3.00 connector might be used for a device with a dollar's worth of electronics. This is not attractive for home use.

When reports of trouble with aluminum wiring were first encountered, NBS was asked to look into the problem. It was found, as one might expect, that many of the reports of difficulties were poorly documented. In some cases, it was suspected that whenever a fire occurred due to unknown causes, it was easier to blame electrical wiring than anything else. Nevertheless, there was considerable evidence, and I certainly saw enough samples of wire brought to us, that showed that aluminum wire does give trouble. Our initial interest in the mechanics of aluminum wire connections reflected the following viewpoint: O.K., the wire creeps and the connection has to maintain pressure on the wire while it creeps.

A. How much does the wire creep in thickness?

B. How much spring is there in the connection to follow this creep?

We were told by industry representatives that they had not tested the wire itself for creep, but had tested the aluminum from which it is made. We made creep tests at NBS, applying loads to wire loops in the range applied by nominal screw heads. In one case, creep of approximately 6 mils was observed in the course of a week. In general, as is normal, the initial creep rates tended to be high but decreased with time. This is especially true as round wire flattens and its geometry changes. We found that one aluminum wire was almost as good as copper, but that some wires were very much worse.

We also made some exploratory measurements on the springiness of the connectors, using different kinds of connectors and different techniques to simulate the geometry as it would be with a wire present. Two half-round steel washers were placed between the screw head and the plate, with an open-sectored tapered metal strip between them. After the screw and the washer sandwich were tightened, the middle piece, whose taper was about one-thousandth of an inch per inch, was slowly pulled out. The distance and magnitude of pull required before the connection became loose indicated how much the connection "followed." For example, pulling out two inches before it became loose implied that no pressure would be left at the end of two mils of wire creep. As expected, for small distances the "spring" of the connectors proved to be quite linear, but they could follow for only 3 to 6 mils. The springiness of this kind of connection seems to come mainly from the flat plate, which is dished slightly as the screw is tightened. I suppose that the screw is lengthened very slightly and the head of the screw also acts as a flat spring. (See attached memorandum dated April 21, 1975, from Larry Andrews.)

We did not determine what provided the springiness and it probably doesn't matter as long as the components are made more or less of the same metal. In my judgment, however, the amount of spring in the connection was really not enough to make a good connection. Secondly, I have serious doubts that the CO/ALR device is good enough just because it tests satisfactorily under our over-current tests. I believe that, for the expected creep of wire over the lifetime of a home (perhaps 50 to 100 years), the force on the wire in a good connection should not decrease by more than 50%. For extra safety, one should assume that the wire creeps under constant load which, of course, is not the case in practice. Let us suppose that the wire is tested under constant load, namely the initial load, and the creep is predicted on the basis of such observations over a year or two. (Very simple special equipment can be made just for testing creep of wires.) If the creep is expected to be, say, 6 mils in 50 years, then the connection should be made to follow 6 mils and lose no more than half of its initial force during this period.

In order to examine the connection interface, bonding, etc., further, we embedded some wire assemblies in epoxy cement. We then sectioned the screw, the plate and the wire and we found that the threads were, at best, marginal. Between the screw and the plate the threads were badly deformed; the thread angle was not at all like the original. It is amazing that they don't strip more often than they do. In fact, the instructions to the electrical trade for using a CO/ALR device with #14 copper wire (which gives less friction because of its smaller diameter and because copper has less friction than aluminum) warn that, in tightening the screw as hard as possible, a strong man can easily strip the screw or the thread in the plate. Thus, if the electrician tightens the screw with aluminum or with copper, the screw may be nearly stripped. With appreciable heating of the connection during a summer air-conditioned cycle, the screw might fail mechanically and the loose connection can lead to run-away heat conditions. However, we have not checked this theory by actual tests.

We made some extended tests of various connections and found that the CO/ALR device did, in fact, pass an over-current test where a current of some 40 to 50 amps was passed periodically through the connector and the connector was permitted to cool down, after which it was cycled again, and so on. It is obvious from the test that certainly, as far as laboratory conditions go, the CO/ALR device appears, at least under the conditions which we used and for the period of time which we tested it, to be satisfactory. I am concerned, as I said above, about its being really good enough, because I can conceive of another possible situation which we mentioned in one of our earlier aluminum wire reports.

Consider the scenario of a wire under very heavy stress and the outlet located in an outside wall warmed by the sun. With maximum current drawn, as for air conditioning, even a correctly made joint can become quite hot. The connection as a whole expands, but the wire tends to expand at a greater rate, hence it creeps laterally. The connection may stay tight for the summer, but then the air conditioner is shut off and the wall becomes very cold. The outside temperature may drop well below freezing. Now the wire contracts more than the rest of the connector and the connection may become very loose. A heavy current drain through this poor connection (as by a space heater), or elsewhere along the circuit, causes overheating because the wire is loose and has oxidized by virtue of that looseness. If it survives the winter, the connection is not as good the following summer because of the oxide that was formed and the change in dimensions. It is entirely possible that the connection will become completely unsatisfactory after this type of annual cycling, running away in the second or third summer, or in the second or third winter.

There is another possible source of heat, independent of the connection itself. It is very common for a conventional pronged plug, as used in the United States, not to fit well into the wall outlet. If the current through the plug is appreciable, as with a vacuum cleaner, space heater, or refrigerator, the outlet will get very hot and may even arc continuously. Since the physical connection from one socket of the receptacle to the two screws is one piece of brass, the heat will be transmitted to the wire connection and may act to bring on failure.

It should also be noted that the brass in the connector tends to lose its springiness when it gets hot, as is true of most metals. Brass is not very good in this respect, which means that the spring of the connections, both to the pin plug that is inserted by the user and to the wire, may become worse as the device gets hotter. In other words, all the effects of heat are to make the heat more likely and to increase the voltage drop. Therefore, the temperature rises as the energy dissipated in the connection goes up and the situation gets progressively worse. This is not hypothetical: I have examined plug-pins in my own home which caused overheating of connectors because other members of the household failed to observe or correct bent pins. In fact, either the springs inside the connector should have been corrected or the whole connector should have been changed. Although I do so at home, very few people change the connector when it doesn't feel tight when a plug is inserted. This can lead to trouble, not only with aluminum wiring but with copper wire as well.

It should be noted that a bad connection, not only where the wire joins a screw but a hot joint of any kind (for example, from the outside influence of the pins, or because of the wire itself) can lead to the melting of insulations. Since the group of wires squeezed into the box presses against the side of the box (which may be metal) and wire against wire, shorts become likely. (We have seen cases where the thermoplastic wire insulation has melted for one or two inches back from the connection.) The short-circuit current may be great enough to "blow" the fuse or trip the circuit breaker. (Circuit breakers are better than fuses in one respect - they cannot be bypassed as easily as fuses.) This generally leads to repair of the bad connection. But the connection may not be quite bad enough for breaking the circuit, but be just a poor, high resistance connection, particularly with aluminum wiring.

There is a related heat problem concerning insulated boxes made of plastic. An NBS staff member inspected a house on Long Island where a person died. The boxes were plastic and one had disappeared completely. I would prefer a metal box to contain the heat and cause a definite short if the insulation melts. I feel that tripping the circuit breaker is preferable to the wires melting the box, shorting to each other, and starting a fire due to trash in the wall or wallpaper that's been pushed into the box when the cover was put on. However, current codes permit plastic boxes. The ideal box might be metal with an internal lining to provide electrical insulation but thin enough to be thermally conductive so as to dissipate heat through the box. I think that this is too much to ask, so I would compromise on the metal box for the conventional type of outlet or switch.

If I were today writing a standard for the future, I would require a larger box so that one could put in the connections without using one's foot to drive them in, have enough room for pigtails, if necessary, or minor repairs, and accommodate solid state light controls which are often substituted for conventional switches. (There are other electronic devices to be considered, such as wall switches operated by proximity rather than by contact. People don't like dirty wall switches and would pay a premium for a switch that you don't touch - in fact, just the presence of a human being could turn the lights on. This is not the product of my imagination: companies are working on this and I expect to see them in the very near future.) The boxes therefore must be bigger, particularly for aluminum wire, which is thicker and harder to dress into the box. The box may be made taller if normal horizontal spacing is to be retained, or wider. Also, the wide availability of such boxes needs to be assured.

At this point, I would like to say something about the use of wire nuts with aluminum wiring. Wire nuts work quite well with solid wire and small currents, but with stranded wire or heavy current the story is quite different. If one twists stranded copper wire with solid aluminum wire, as is often done for ceiling fixtures or other equipment with stranded leads, the connection is very poor. The wire nut cuts the thin strands of copper readily and, in fact, often cuts them off and may not bite into the aluminum wire at all because of the overlay of copper wire.

If I had to connect a stranded copper wire to an aluminum conductor in a box, I would first connect a solid copper wire to the aluminum wire. I would then connect the solid copper to the stranded copper with another wire nut. As a matter of fact, it would be very convenient if the fixtures came with solid pigtails already connected. Unfortunately, the length of leads cannot be predetermined, particularly for ceiling fixtures which must be "dropped" before you can connect them. Perhaps a foot of flexible lead is needed and stranded copper is almost universally used there. Pigtailing is probably the correct technique here. One could design special crimp connectors for stranded wire but, again, the objections to crimp tools, techniques, and inspection would still apply. I would rather have a wire nut that I can remove, inspect the joint, and then restore.

There has been widespread use of wire nuts in very heavy current circuits. In a Montgomery County, Maryland community, for example, heavy wires were brought into electrical heating systems that required some 40 amperes. Improper connectors were used and various kinds of failure have occurred. In such cases, the inspector or worker (usually from the utility company) installs a saddle connection where the wire lead and the lead from the heating system are inserted into the saddle, the bolt is tightened and the whole thing is heavily taped, making quite a good connection. Wire nuts should certainly not be permitted in such applications.

Some Experimental Connectors

In order to get a better feel for the problem of wire creep, we made up some experimental connectors, including some where the wire was captured between a screw undercut in the exact shape of the wire and the plate cut in the other sense, so that the wire lay in a closely fitting groove (See Figure 1). A lead-in groove in the connector kept the wire lead-in from being cut by the two close fitting grooves. The connection was very good; the wire did not seem to creep. We tested them at high temperature to detect any looseness when cycled or heated well above what any connection should stand, i.e., several hundred degrees C. Although some became corroded, they stayed tight. Theoretically, the wire can creep in such a connection, but only lengthwise. Such creep length is very great and the wire has to creep along the surface, so that the high friction of the wire keeps it from creeping. Obviously, if one uses a long wire and holds it for its entire length, the end creep - the longitudinal creep - will be very small; if the pressure is high, the friction forces are also very high. The screws recovered from these tests are white where they contacted the wire. In other words, we rubbed off enough aluminum to make a good bond between the aluminum and the brass of the screw.

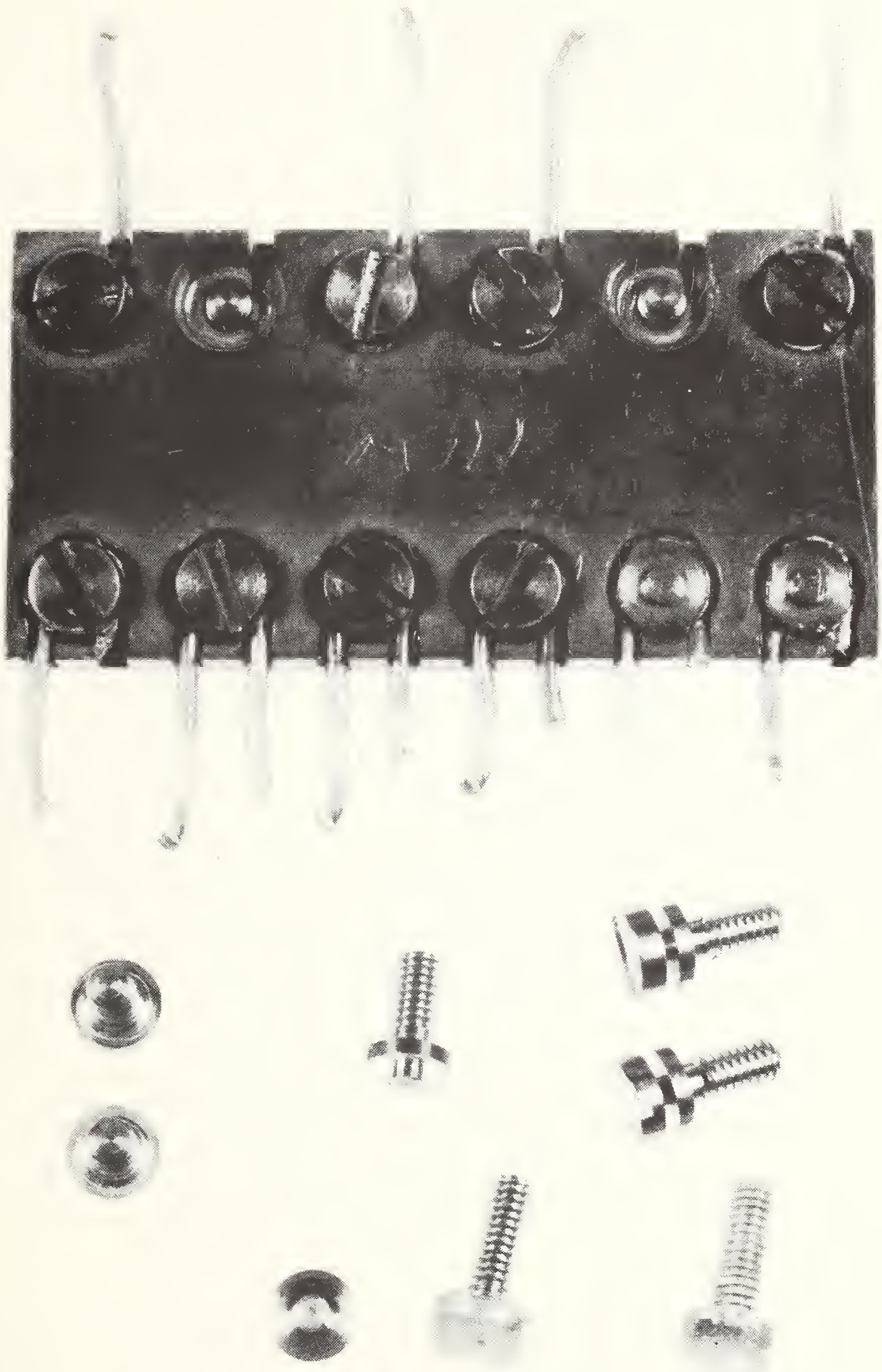

Figure 1 - Experimental connector designed for a particular size of aluminum wire. Also shown are special screws, the heads of which are sheared off when the proper tightening torque is reached.

I also wanted to design a screw to control the fastening torque independently of the skill of the operator. I had the NBS Shops Division make up some double-headed screws where the upper head would be stripped off when the specified torque (about 12 inch-pounds) was reached. The lower head for the working section of this type of screw is unslotted, so it should have a hexagonal shape for later removal, when necessary, with a socket wrench. (These are not original ideas; at one time a U.S. manufacturer made screws on a continuous string, with each screw driven by the next. The screw tip was sheared off when the head of the screw ahead was bottomed, and the whole string of screws was driven by a socket wrench. Feeding was easy and the torque was controlled by the shearing forces. Nuts are also made this way and this art is old.) An alternative to the double-headed screw might be a molded plastic head over a standard screw (also shown in Figure 1). This head could be stripped off by the screwdriver. A screw without the plastic head implies that it was tightened correctly, at least once, although not necessarily subsequently.

During our work on the connectors, we discovered, somewhat to our surprise, that about three-fifths or four-fifths of the current flowing from aluminum wire to the screw terminal flowed through the screw while the remainder went directly to the plate. (General Electric engineers told us that they knew this.) The obvious explanation is that the screw scratches the wire and wipes off the oxide; the surfaces don't slide against each other very well so the contact between the screw head and the wire is rather intimate. This does not occur between a plate and a wire where no rubbing occurs. This is why one gets a better connection if the plate is serrated. This brings me to a rather interesting development of one manufacturer who made a washer that was U-shaped so that it could be slipped over the screw without the (usually captive) screw being taken out. The washer, of a hard brass alloy, had teeth on both sides like those on a wood rasp. The washer was put over the plate of the connection, the aluminum wire put over the washer, and the assembly was tightened conventionally. This passed the UL test for wiring, but the manufacturer did not want to sell the washer and UL does not approve them. The reasoning is very interesting and important to our discussion. The washer wasn't deficient as a fix for the problem of aluminum wire because it bit into the plate below and the wire above, producing a good connection. However, a person making a connection may leave out the washer or place it above the wire (a customary site for a washer) - in the latter case, the screw could not be turned at all or only with great difficulty; the pressure would be low and the wire might be wrapped around or torn to bits. It was an excellent washer electrically, but not a good washer from the point of view of human factors.

I touched on this subject of human factor connections with crimp connections and, of course, this is a problem that rises in connection with all tools and equipment that people have to use and certainly with the things they have to do in wiring. The double-toothed washer did not go on the market because of human factors, not technical factors. Any similar device should be designed so that the human operator can't easily foul up the intent. This led me to design a connector, shown in Figures 2 and 3, where the wire was to be placed between two sections of the same brass sheet and the screw was not part of the circuit. I put one Belleville washer under the screw head and one under the nut. In fact, the nut could be a Belleville washer itself. The advantage of two Belleville washers is that they have considerable distance of spring force for following the creep of the wire. The screw for this connector can be steel, saving money and preventing stripping; more thread can be provided in the nut than the single thread in a piece of brass. Another advantage of this connection was not obvious at first: the contact between a Belleville washer and the screw head above it is right next to the stem, at a small radius. The frictional torque is initially relatively low, so that the screw is easy to drive. When the washer suddenly flattens, the friction force shifts to the outside rim of the head; the torque increases suddenly and "bottoming" is sensed. This indicates that the Belleville washers have been compressed and the limit reached. As a further advantage, visual inspection, without removing the outlet from the wall, can reveal that the washer is compressed and the force on the wire is correct and, therefore, that the connection has been made and tightened properly. This seems to be a good criterion for all connections: they should be visually, or at least easily, inspectable. A visual inspection, without removing the device from the box, is attractive, especially because inspectors don't like to carry tools or use gadgets. This has some bearing on my following remarks about crimp connections. When the NBS Patent Adviser's Office made a patent search on the idea of Figure 2, the idea was found to be old. It was described, almost exactly as I designed it, by Patent No. 1,296,061 issued in 1919!

Many other ideas have occurred to us and the possibilities for inventions are endless. For example, outlets and switches have been made with pigtails attached. Such pigtails could be connected, if they are made of solid wire, to aluminum wire or to other copper wire by wire nuts. This should certainly be a great deal easier than using screw terminal connections. Another possibility is to provide studs on the back of an outlet or a switch or a circuit breaker that would be, say, about an inch long to which a wire could be connected with a wire nut. This stud should be no longer than necessary; it would be directly in back of the device so it would not require side space and if the device is properly designed there should be enough room behind the device to handle this connector. If wire-wrap were possible for thick wire, then such studs could be used with proper wire-wrap tools.

Another idea would be a device, such as shown in Figure 4, where one simply inserts a wire into a hole and turns a screw which wedges the wire into the connection. The screw, which could be self-tapping, would bite into the wire and bite into the wall of the structure so as to wedge both itself and the wire and deform the wire in the process. I have used such a set-screw to hold the small wheel onto a shaft where the wheel had to

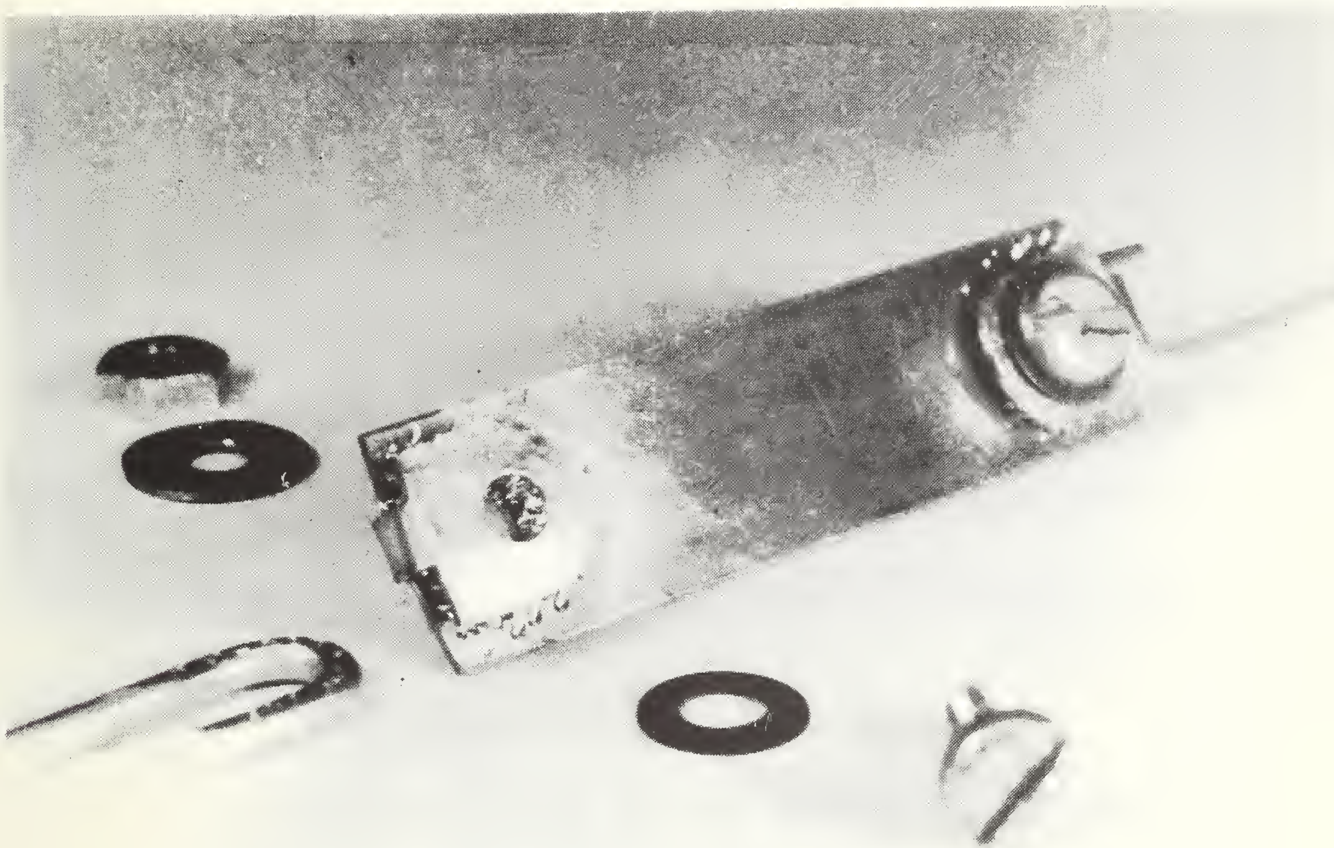

Figure 2 - Experimental connector for aluminum or copper wire designed to be used with Belleville washers so as to compensate for the creep of the wire. The screw does not carry current.

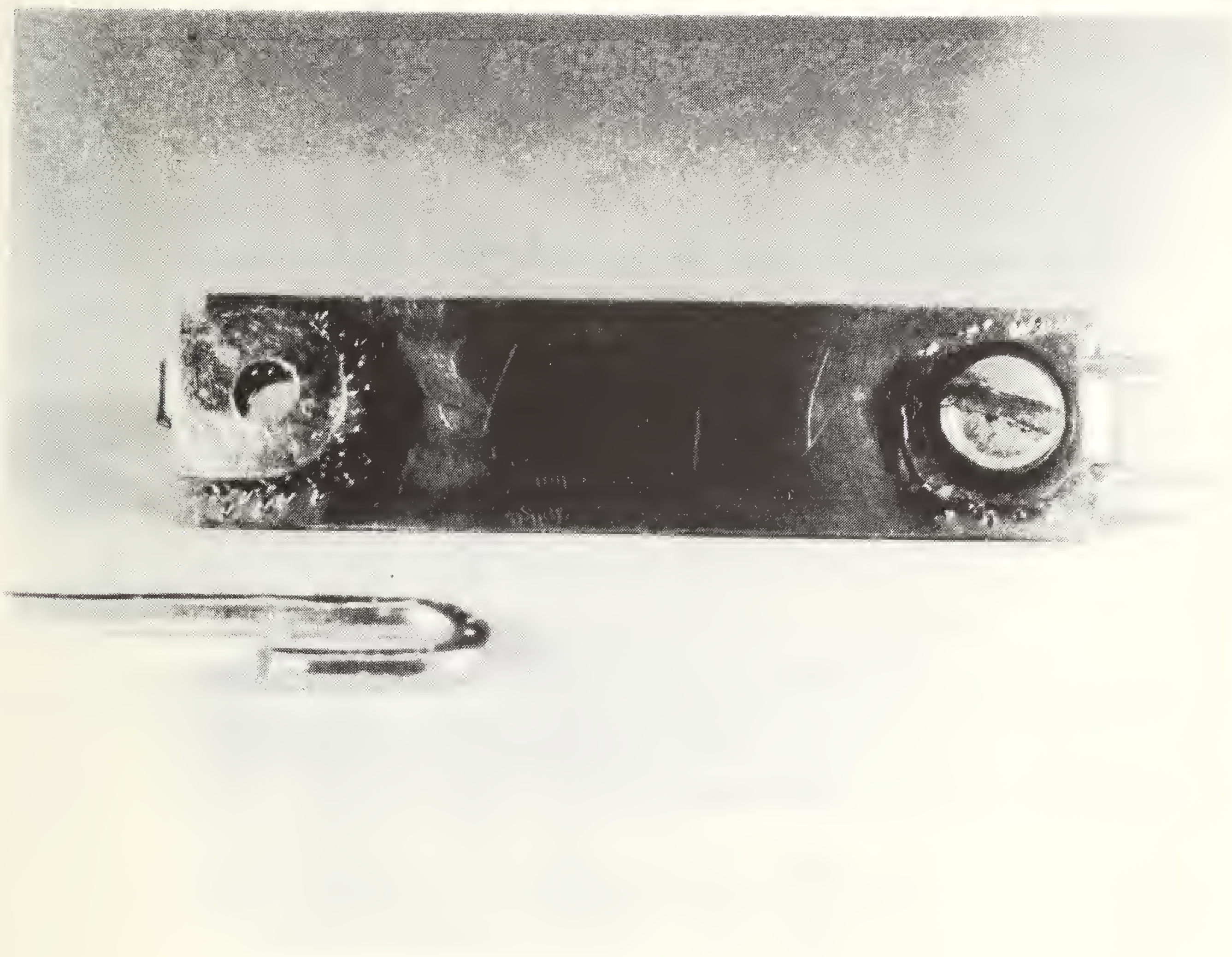

Figure 3 - Another view of the connector in Figure 2.

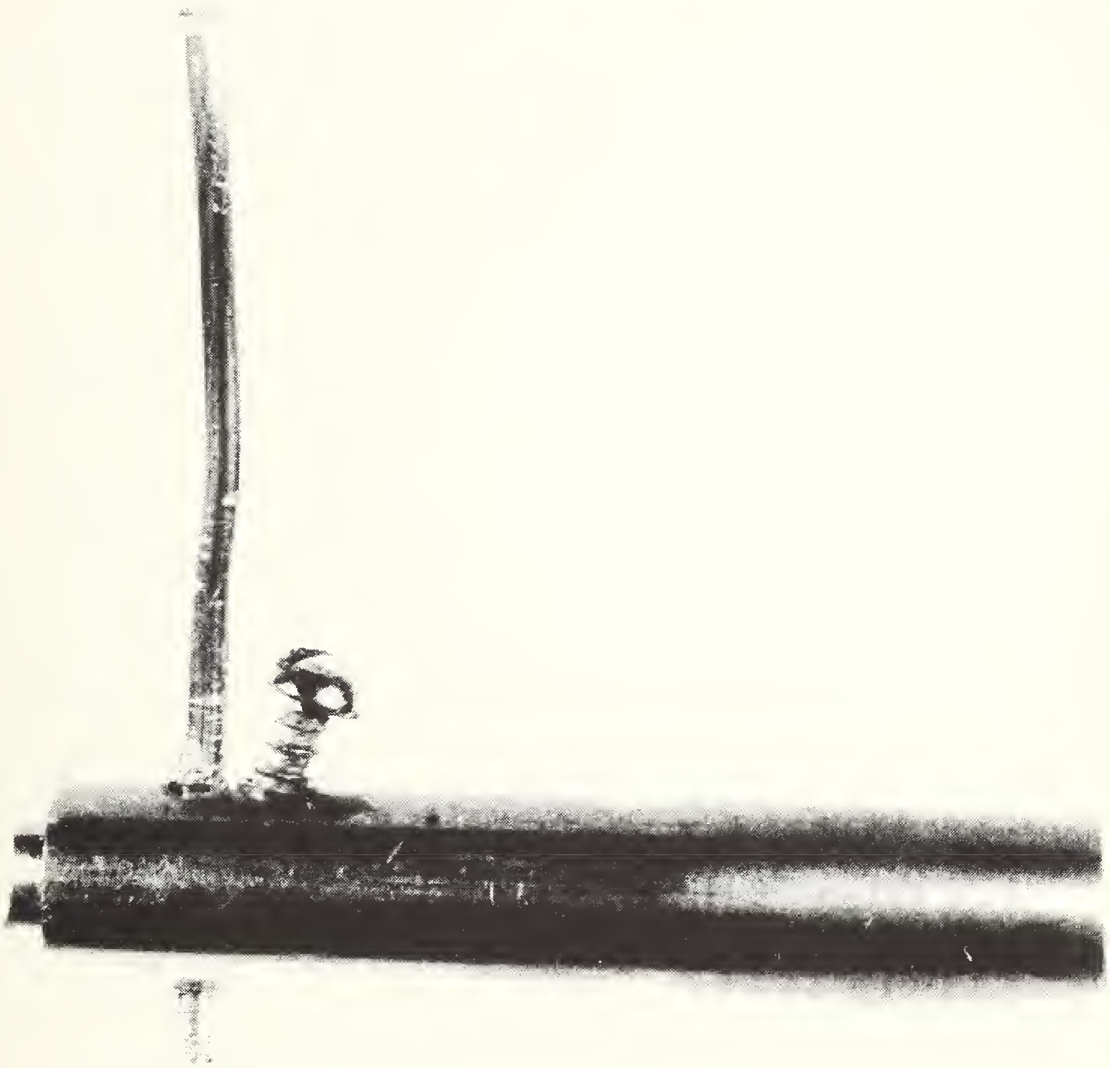

Figure 4 - Experimental connector for wire using a screw wedge.

spin at very high speeds and where I did not want the outside surface of the wheel to have any set-screw holes. By using two set-screws, one on each side of the wheel, the wheel remains balanced and the wedging of the set-screw against the shaft, as it would do here against the wire, held the system very tight. In the photograph of Figure 4, I show a conventional screw with a regular screwdriver head, but it could be a set-screw with a head for a socket wrench. This would make the whole thing much more compact and the set-screw could be nearly flush with the surface of the connection. In the design shown, the wire is perpendicular to the device and the screw is at an angle; the components could be interchanged so that the screw would be perpendicular and the wire come in at an angle. In this particular version, I threaded the hole into which the wire fits so as to produce a serrated surface and to cut through the oxide of the wire. The connection was not tested; it was made just to get the "feel" of such a construction. It certainly is easy to use and the wire is held very firmly.

While on the subject of set-screws, screwdriver heads and so on, I would like to stress another point which relates to the present screwdriver slot, a historical misfortune in many ways. The slots are easy to make by a milling cutter in automatic screw machines, but most modern screws are no longer cut on screw machines: they are forged out of solid material, thus eliminating waste. A socket head can easily be upset on a forged screw. Hexagonal sockets are most common, but they require an accurate fit between the wrench and the socket and high quality of steel. For electrical connectors, I would prefer a square socket hole, such as the Canadians use for electrical wiring. I do so for several reasons. First, it is easy to manufacture by an upsetting machine. Secondly, the screwdriver blade is a very simple square shaft. (Screwdrivers, as a matter of fact, often start with square shafts and then are forged or shaped into the wedge blade with which we are familiar.) A square shaft does not require close tolerances to drive properly; it is very easy to grind when the edges get rounded. It's much harder to properly sharpen a conventional screwdriver. Also, a socket driver - particularly when driven by a motor - does not fall out of the slot and gouge the surroundings.

Among other considerations, if socket screws are adopted for a new generation of devices, a glance at an installed device (or one on the store shelf) would show that this is the latest, improved type which meets the newest code. It is important that the inspector not have to take it out to locate special markings (e.g., "CO/ALR 2"). Incidentally, a square socket can be driven with a conventional screwdriver of the right size although this isn't the recommended procedure. I think that every home mechanic now has at least one set of socket wrenches, and one additional set can have square shanks. Very few sizes would be needed.

While this report is concerned with wiring, in general, and not only with fixes for homes that have old-fashioned connectors and old type wire, I would like to come back to a fix that is being proposed and seriously considered, and that is to use crimp connectors as a general fix for houses that have aluminum wiring. I also have the feeling that the proposal to use crimp connections is intended not only as a short-term fix, but also as a permanent part of a standard for the future. The whole idea of going to crimp lugs doesn't make much sense to me.

For older homes, expensive makeshifts may be justified. A standard for the future rightfully should not specify an expensive system which uses extra parts, extra gadgetry, and very special tools, especially if there are other possible approaches. We understand that various companies are working on new outlets, new switches and new contacts, and their engineers admit freely that they could certainly make better connectors than the 20-30¢ items now produced. It seems to me that the industry should be asked to come up with better connections even if CO/ALR devices are good enough, as our tests show. In spite of my doubts, I could not swear in court today that the CO/ALR connection isn't good enough. The fact that I may be suspicious of the springiness of the connections, or that the threads can be stripped, is insufficient reason to outlaw them. If I had properly installed, indium plated, CO/ALR devices in my house, particularly with nickel plating under the indium, I would sleep easy and not worry.

With regard to indium plating, I talked to its inventor. He definitely believes that indium is necessary, apparently because it protrudes or extrudes through the cracks of the oxide and, by whatever means, makes good connection to the aluminum. He was also sure that the indium should be underplated with nickel. The laboratory where he worked tried various other metals, but nickel keeps the indium from interdiffusing with the brass or copper alloy and stays soft for many years. We made rather limited tests using interdiffused indium; that is, we interdiffused it by accelerated heat tests and the connections still stood up. That was not too surprising because the CO/ALR devices work quite well without indium although the resistance is somewhat higher. Additional testing is probably required but, to play safe, I would take the advice of a man who obviously spent a great deal of time and money on this, and demand nickel plating under the indium of CO/ALR devices.

Having noted some of the difficulties with crimp lugs that do not fit many old-time devices and do not fit well into the new CO/ALR equipment, I would strongly advise our decision makers not to use crimp connections for aluminum wire. This would require the abandonment of most CO/ALR devices used today in favor of old-style devices without the wire capturing lugs, hopefully with such devices converted back to original shape except that they would use brass screws. All of the CO/ALR devices in production and stocked by dealers, electrical supply houses, and electricians would have to be abandoned if crimp lugs are to be used and there would be a tremendous quantity of these throughout the country by the time a standard on crimp connectors would go into effect. In general, this is an expensive and difficult way to go.

Knowing the difficulties encountered with the simple toothed washers and in tightening ordinary screws correctly with a screwdriver - or forgetting to tighten - can we expect tens of thousands of electricians (professional and amateur), piece-workers, and pick-up people to use expensive tools correctly?

In any case, I doubt if there are enough tools to supply the American requirements for quite a few years to come. I am very sure that people will use inappropriate terminals, either wittingly or unwittingly. Many people will simply use a pair of pliers for clamping rather than making an effort to buy or borrow the right tool. Although I'm a careful worker and know where I can borrow the right tools, and in spite of the fact that I once designed watches, I confess that to regulate a watch I open it with a pair of pliers or use some other makeshift tool to get into the notches in the watchcase to unscrew it. If I do this to a watch, I certainly will not go out to buy a special tool and the correct lugs to connect a wire. Then, too, the people who rent the tools may not sell the appropriate crimp lugs, and so on.

Other Concepts

We also investigated alarm systems rather than wire fixes. For example, there's a company near this city that makes indicators for frozen foods. These change color when a package of frozen food has been defrosted. They made up a number of similar indicators, to be attached to the cover of an outlet box, that would permanently change color if the temperature of the box rises beyond a preset value (see Figure 5). We tested such devices and found no technical problems. The difficulty is that many outlet boxes are hidden by furniture or drapes, so the color warnings may not be effective.

I also suggested the use of a plastic covered pellet that would melt at some temperature, say 100° C or perhaps less, and release a pungent odor. If one is worried, he can open a box, drop in a pellet (assuming that it's nonconducting), then close the box. At least this is better than simply worrying about the problem.

There are valid objections to such suggestions, and I agree with the general philosophy that the connection should be good in the first place, and that such makeshifts are undesirable. According to the same philosophy, crimps should not be adopted either because they, too, are a makeshift. It does not seem sensible to take a wire which can be connected directly to a device and interpose another device rather than building the connector into the device itself.

Conclusions

I believe that it is time for the manufacturers and installers of electrical wiring in homes to use equipment which is compatible with our advanced technology - something which I believe our present outlets and switches are not.

I think that the industry should design the connections in such a way that inspection is easy because I have great doubts that inspectors spend enough time and effort to inspect the present connections. By this I mean that it should be easy to open the box and look inside to see whether (a) the piece of equipment is the latest correct type, and (b) whether it was properly used.

I believe that a standard for home wiring should cover copper as well as aluminum wire because many homes have both aluminum and copper wiring and aluminum may replace copper if copper becomes in short supply again. I think that all connectors and all switches should be usable with either copper or aluminum and I do not see how one can justify two different kinds if the cost difference between them could be small. Since the labor for installing them is so expensive now, a differential of, say, 10% in the cost of the device should have an insignificant effect on the total cost of the home or even a single repair installation. As a matter of fact, good connectors for aluminum, as far as I know, without exception also make good connectors for copper and, therefore, a common standard should specify equal performance and equal design for both, except where absolutely necessary to indicate a difference.

In general, the quality of workmanship, ease of inspection and other aspects of wiring should be universal and poor connections for copper should not be tolerated any more than poor connections for aluminum. Also, many mistakes can and will be avoided if a customer can buy only one kind of outlet or switch; that is, one which can be used with any wires so he or she doesn't have to make the right match. If two or more options are available, there is a significant chance that the wrong one will be used due to carelessness, greed, ignorance, or stupidity of the buyer.

While I understand the reasons for the drive to produce some quick fix to take care of houses which have aluminum wiring of the old type and connections of even older type, I think that the Government should not endorse a solution which is known to be merely a stopgap and which is likely to become permanent.

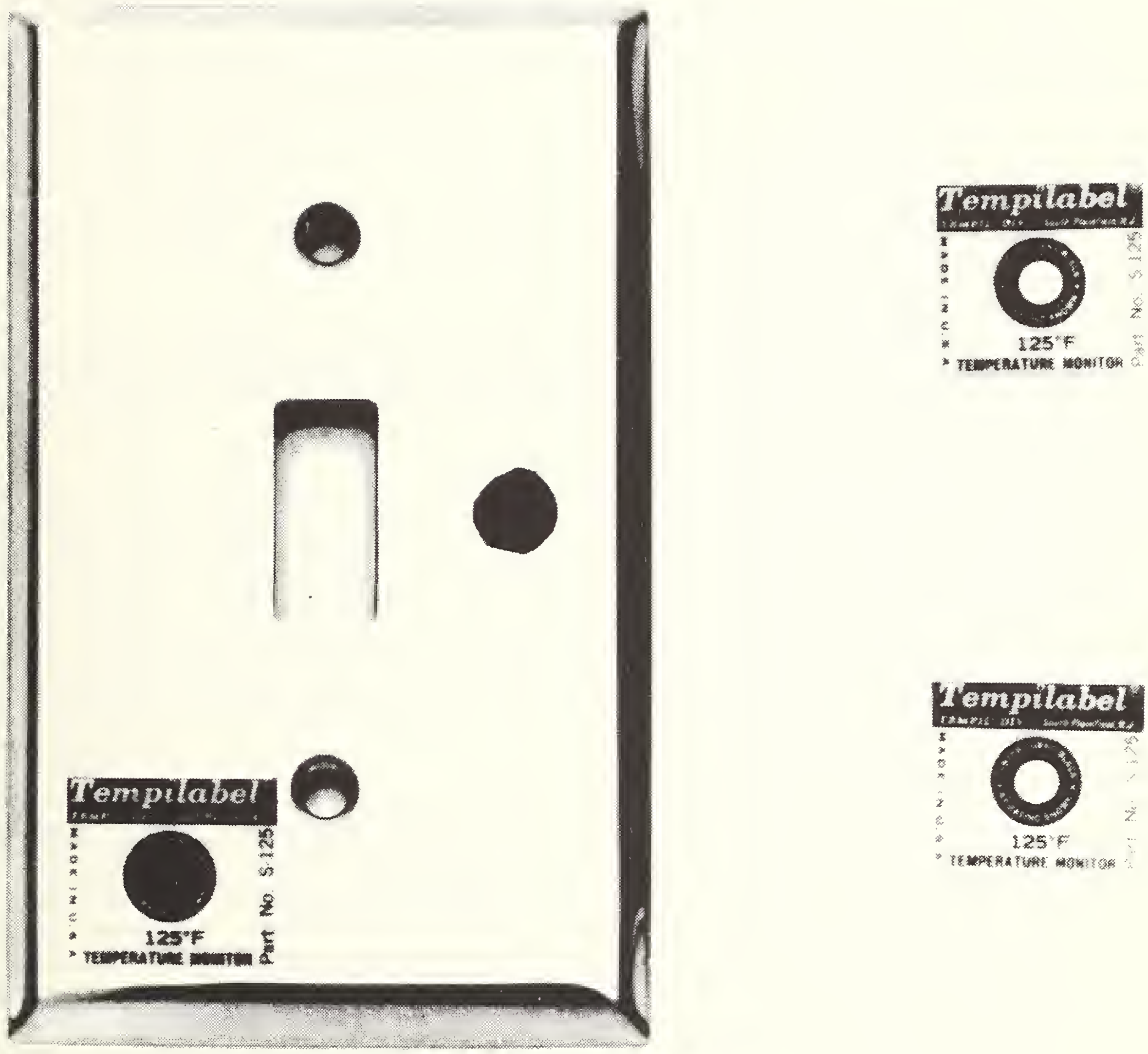

Figure 5 - Heat indicator for a wall plate over a switch or wall socket. The color of the indicator changes at the pre-set temperature of 125° F.

UNITED STATES DEPARTMENT OF COMMERCE
National Bureau of Standards
Washington, D.C. 20234

April 21, 1975

MEMORANDUM FOR Sid Greenwald

From: Larry Andrews

Subject: Screw Compliance of Electrical Outlets

The effect of plastic flow in reducing the clamping force on a wire depends upon the springiness or compliance of the screw and plate combination. The following experiments were made to determine the magnitude of this clamping compliance in some typical electrical outlets.

Rather than measure screw-plate deformation directly as a function of axial screw pressure, the screw torque was measured as a function of angular position of the screw. This is a very simple measurement to make and avoids considerable instrumentation. This approach is reasonable if the coefficient of friction is constant and the screw lead is uniform. To minimize the effect of initial plastic flow of the threads on screw and plate during initial loading, the screws were tightened several times until repeatable torque-position cruves were obtained.

Measurements were made on four types of regular duplex outlets and one CO/ALR outlet. Wherever possible, hardened steel washers were used under the screw heads in place of a loop of wire. These washers were equivalent in thickness to number 12 wire and were beveled to simulate the shape of a round wire. Washers could not be used on the "D"* outlet. It was therefore measured using a loop of hard brass wire. Two things were noticeable about the "D" outlet with this type of screw load; the screw appeared to have considerable more compliance, and it was more difficult to obtain repeatable results. To determine what effect the use of the loop rather than full 360° washers had in modifying the screw-plate compliance, the "C" outlet was re-measured using the same loop. The results for all five outlets are shown on the enclosed graph. The zero strain point on each of these curves is strickly arbitrary. On most of the outlets it requires about three inch-pounds of torque before a linear stress-strain region is reached.

As tested with steel washers the outlets showed considerable range in compliance. For example, the "A" heavy duty indicated only about 0.6 mils compliance between 5 and 10 in-lb torque, whereas the regular "A" outlet had over 1.5 mils.

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*The letters "A" to "D" refer to four different manufacturers

Measurements on the "C" unit indicated that the compliance with an actual loop of wire may be considerable higher than that with a washer. With the 360° washer the compliance between 5 and 10 in-lb torque was only 1.2 mils. With the wire loop, which contacted about 270°, the compliance was about 2.2 mils.

On the other hand, CO/ALR units should not have appreciable more compliance than older outlets with the same plate design. Measurements were repeated on the stiffest unit - "A" heavy duty - with brass in place of the steel screw with nearly identical results.

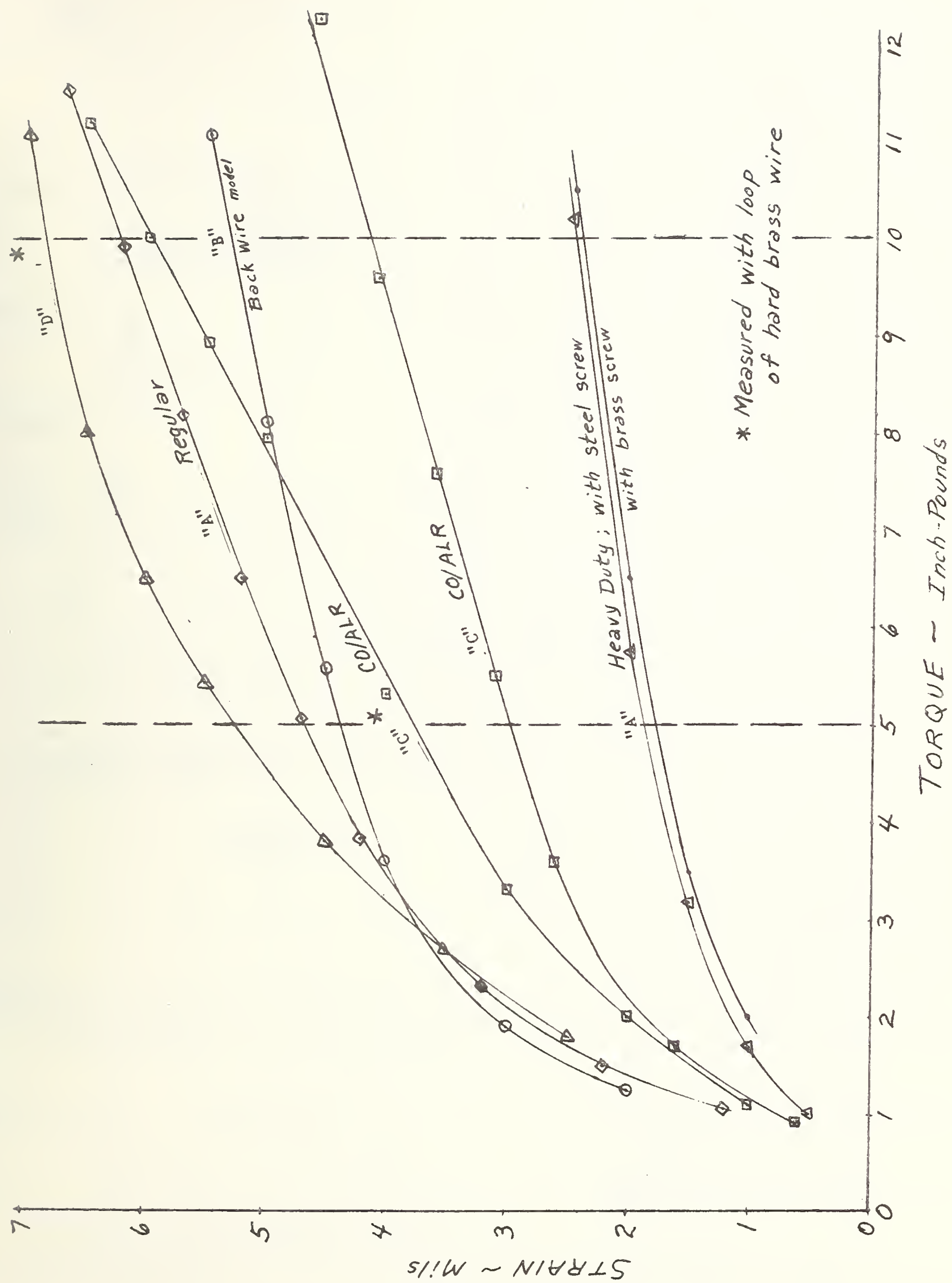
The screw-plate compliance, as measured between 5 in-lb and 10 in-lb, for the various outlets tested are as follows:

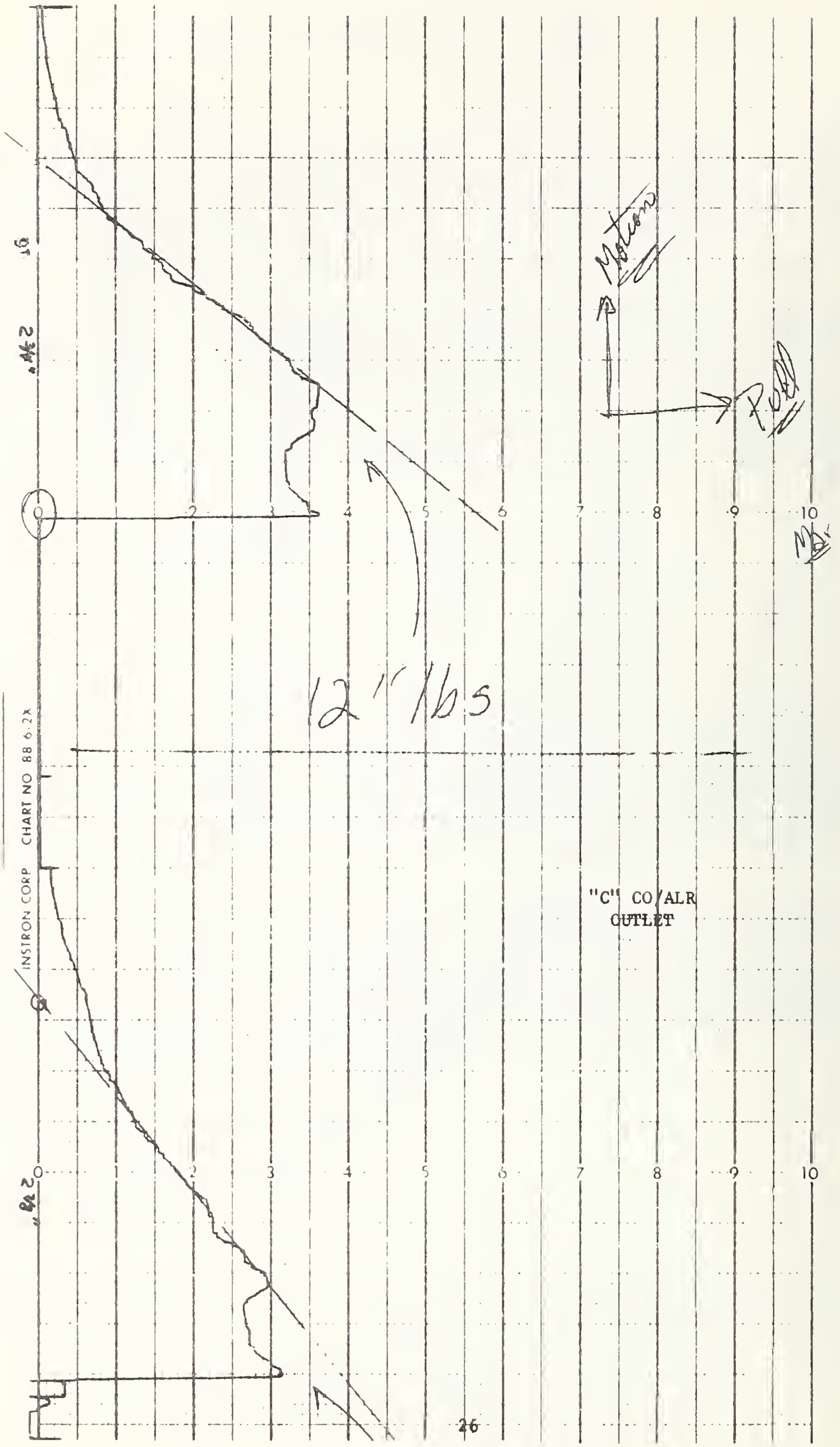
"A", heavy duty	0.6 mils
"A", heavy duty with CO/ALR screw	0.6 mils
"B", back wired	0.95 mils
"C", CO/ALR	1.2 mils
"A", regular	1.55 mils
"C", CO/ALR, with brass loop	2.2 mils
"D", with brass loop	1.6 mils

Compliance measurements were also attempted by means of measuring the pull force required to withdraw a thin tapered wedge from under the tightened screw head. For this thin hardened steel wedges were made with a taper of one mil per inch. Pull force as a function of motion was measured on the Instron tester. Again, beveled steel washers were used on each side of the wedge to simulate thickness and shape of No. 12 wire.

Unfortunately, the friction and therefore the pull force was rather unstable for about the first inch of motion. Results of two such tests with the "C"-CO/ALR outlet are shown on the accompanying chart. From the slope of the most linear portion of these curves the compliance can be estimated to be 0.24 mils per inch-pound differential which agrees with the previous experiment.

Attachments


"D"
Regular
"A"
"B"
Back wire model
CO/ALR
"C"
"C" CO/ALR
Heavy Duty ; with steel screw
with brass screw
"A"
* Measured with loop
of hard brass wire
TORQUE ~ Inch-Pounds
STRAIN ~ Mils
0
1
2
3
4
5
6
7
8
9
10
11
12


INSTRON CORP CHART NO 88 6-2X
0 2 3 4 5 6 7 8 9 10
12"lbs
Motion
Pull
"C" COLLAR
OUTLET

NBS-114A (REV. 7-73)

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15. SUPPLEMENTARY NOTES

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

This report is a subjective and personal statement of my experiences and thoughts regarding electrical connections, in general, and aluminum wiring for homes, in particular. It is not a statement of official position of the National Bureau of Standards (NBS). It is entirely possible that other members of the NBS staff may not agree with many statements made in this report. It is based on some considerable experience and where the ideas expressed are not based on such experience, I hope this is clearly indicated.

My conclusions are that present day technology of electrical distribution wiring in residences is not in keeping with good engineering practices available today. This is true relative to both copper and aluminum wiring.

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

Aluminum wiring; Electrical connections; Pressure terminals; Wire creep

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