FINAL REPORT

on

INVESTIGATION, TESTING, AND SELECTION OF SLIP-RING LEAD WIRES FOR USE IN HIGH-PRECISION SLIP-RING CAPSULES

to

GEORGE C. MARSHALL
SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

September 15, 1966

by

R. H. Ernst, D. N. Williams, and E. S. Bartlett

BATTELLE MEMORIAL INSTITUTE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

Battelle Memorial Institute · COLUMBUS LABORATORIES

505 KING AVENUE COLUMBUS, OHIO 43201 · AREA CODE 614, TELEPHONE 299-3151 · CABLE ADDRESS: BATMIN

September 21, 1966

Purchasing Office
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama 35812

Attention PR-EC

Dear Sir:

Enclosed are 12 copies plus one reproducible copy of our Final Report on NASA Contract NAS8-20188, "Investigation, Testing, and Selection of Slip-Ring Lead Wire for Use in High-Precision Slip-Ring Capsules".

We believe the substitution of the best silver alloy developed in this program, Ag-1 Cu-0.2 Ni, for silver-plated copper in lead wires will not only eliminate the threat of "red plague" but will also increase the reliability of slip-ring devices through the silver alloys' improved resistance to mechanical breakage.

This has been a most interesting program and we hope that we may again serve NASA in accomplishing their research objectives.

Very truly yours,

E. S. Bartlett

E. S. Bartlett
Chief
Nonferrous Metallurgy Division

ESB:ims
Enc. (12 plus 1 repro)

cc: Mr. Estel G. Lowe
Astrionics Laboratory
George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Huntsville, Alabama 35812

Mr. R. W. Cashman
Hudson Wire Co.
Ossining, New York

Mr. L. C. Decker
Philadelphia Insulated Wire Co.
Moorestown, New Jersey 08057

cc: Mr. E. W. Glossbrenner
Poly-Scientific Division
Litton Precision Products, Inc.
Blacksburg, Virginia 24060

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INVESTIGATION, TESTING, AND SELECTION OF SLIP-RING LEAD WIRES FOR USE IN HIGH-PRECISION SLIP-RING CAPSULES

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SUMMARY

The reliability of slip-ring devices has long been plagued by lead-wire problems. As recently as 1962, breakage of conductors was the most serious problem. However, the use of stranded silver-plated copper for lead wires, since 1962, significantly decreased the frequency of lead-wire breakage. Unfortunately, silver-plated copper lead wires are subject to "red plague", an insidious type of galvanic corrosion, which can produce lead-wire failures. As a result of the demands of the Saturn mission for increased reliability from slip-ring devices, NASA requested that Battelle select or develop highly reliable materials for slip-ring lead wires. Preliminary consideration of candidate materials revealed that new conductors for lead wires should be based on silver. Furthermore, a survey of the properties of commercial silver alloys showed that one alloy, Ag-1.5 Cu, may be useful for lead wires, but its properties were not thought optimum for the lead-wire application. Therefore, Battelle conducted a research program to develop a new silver-base alloy specifically for slip-ring lead wires.

Thirty experimental silver alloys were evaluated in compliance with lead-wire requirements. The best three alloys, A (Ag-1.5 Cu), B (Ag-0.2 Ni), and C (Ag-1 Cu-0.2 Ni), and pure silver were scaled-up to 19-strand, 42-gage, Teflon-insulated lead wires for complete evaluation by NASA.

All the scaled-up silver alloys have excellent corrosion resistance. In an environment of water-2 percent hydrofluoric acid-5 percent sodium fluoride, thought to be much more corrosive than conductors encounter within Teflon, the silver materials did not corrode after 1,512 hours. The silver alloys are also very fabricable as shown by the ease of fabricating them to 19-strand, 42-gage lead wires. The alloys are resistant to reactions with Teflon during curing of the insulation. Likewise, their properties were not affected by exposure to air during the Teflon-curing cycle.

While an oxide film was formed on copper-containing Alloys A and C during the Teflon-curing cycle, the oxide did not degrade any properties studied during this program, including solderability. Furthermore, the thin oxide may be advantageous by preventing bonding of strands during Teflon curing, leading to significantly increased flexure life. Also, the oxide film may retard "wicking" of solder under Teflon insulation, a frequent problem in lead-wire use.

The 30-ksi ultimate strength and the 90 percent IACS electrical conductivity (minimum values) desired by NASA in lead-wire conductors were met or exceeded in the scaled-up silver alloys. Although the alloys have flexure-breakage lives below the life desired by NASA, the flex lives are as much as 2.4 times the flex life of the silver-plated copper lead wires presently used.

Properties of the new silver-alloy lead wires are compared in Table 1 with those of pure silver and silver-plated copper. As shown in Table 1, Alloy C in the partially annealed temper has higher strength than silver-plated copper combined with a flex life 2.4 times that of silver-plated copper. Alloy C in the fully annealed temper and Alloy A have about the same ultimate strengths as silver-plated copper but have higher yield strengths and much greater flex lives. Alloy B just meets the 30-ksi strength target but also has a flex life superior to silver-plated copper. As shown in Table 1, the properties (except for electrical conductivity) of the silver alloys greatly exceed the properties of pure silver. Also shown in Table 1 is that the silver materials have excellent electrical conductivities, 95 percent IACS or better.

TABLE 1. PROPERTIES OF 19-STRAND, 42-GAGE LEAD WIRES OF THE SCALED-UP SILVER MATERIALS AND OF SILVER-PLATED COPPER LEAD WIRE[a]

Property	Pure Silver	Alloy A (Ag-1.5 Cu)	Alloy B (Ag-0.2 Ni)	Alloy C (Ag-1 Cu-0.2 Ni), Fully Annealed	Alloy C (Ag-1 Cu 0.2 Ni), Partially Annealed	Silver-Plated Copper
Ultimate tensile strength, ksi	18.7	33.2	29.7	33.0	35.3	33.4
0.2 percent offset yield strength, ksi	12.8	26.2	19.4	28.4	30.1	24.0
Elongation, percent in 10 inches	13.4	16.5	28.3	28.4	18.5	25.6
Flexure breakage life, bend cycles[b]	39	89	51	86	102	42
Electrical conductivity, percent IACS	103	95	102	95	95	100

(a) Stranded cables were evaluated after removal of the Teflon insulation.
(b) Wires were bent through an angle of 95° over a 0.025-inch radius while supporting a 200-gram load. Tests were conducted at a rate of 6 bend cycles per minute (a cycle is a bend through 95° and return to 0°).

Based on fabricability and properties, Alloy C in the partially annealed temper is judged by Battelle as the best lead-wire candidate. Alloy C in the fully annealed temper is judged the second best candidate followed by Alloy A, Alloy B, and pure silver.

Substitution of silver Alloys C or A for silver-plated copper in slip-ring lead wires is expected to greatly improve the reliability of slip-ring devices. Not only will the threat of "red plague" be eliminated but the increased strengths and flexure-breakage lives of the silver alloys should result in significantly better resistance to conductor breakage. Use of Alloy B for lead wires will also eliminate "red plague" and result in about the same breakage resistance as presently encountered with silver-plated copper.

INTRODUCTION

Corrosion of silver-plated copper lead wires used in slip-ring assemblies of the Saturn guidance and control systems has posed a serious reliability problem. Under certain conditions of plating defects, moisture, and temperature, galvanic corrosion of the copper conductors can produce structural failure of the lead wires and open circuits. Because of the typically red color of the cuprous oxide corrosion product coupled with the damaging effects, lead-wire corrosion has been described as the "red plague".

To eliminate the reliability threat of red plague, NASA requested that Battelle select or develop an alloy that could be substituted for silver-plated copper in slip-ring lead-wire applications. Since the galvanic corrosion problem is, to some extent, always possible when different metals are in contact with each other, NASA requested that new lead wires should not be plated. The slip-ring lead wires used in NASA applications must have a very high electrical conductivity, at least 90 percent IACS. Only alloys based on copper or silver can be expected to have this high electrical conductivity. Furthermore, the ductility and electrical conductivity of unplated copper and its high-conductivity alloys are degraded by the thermal treatment required to cure Teflon insulation, which is used in common applications. Therefore, the use of silver or silver-alloy wire appears to be the most promising way to eliminate lead-wire failures.

The research program described in this report was undertaken to select or develop a silver alloy to replace silver-plated copper in lead-wire applications. Target properties specified by NASA for the silver-alloy lead wires were

(1) Minimum electrical conductivity of 90 percent IACS (maximum specific resistivity of 1.92 microhm-cm)

(2) Minimum tensile strength of 30,000 psi

(3) Ability of 19-strand, 42-gage Teflon-insulated wire to withstand at least 400 bends of 90 degrees or more over a 0.025-inch radius while supporting a 200-gram tensile load

(4) Ability of wire to withstand corrosion due to galvanic action, oxidation, soldering, or welding

(5) Good fabricability, solderability, and weldability.

Research on this program was conducted in the period July 1, 1965, to August 31, 1966.

SELECTION OF CANDIDATE ALLOYS

Survey of Commercial Silver Alloys

A survey of commercial silver alloys revealed that one alloy wire, Ag-1.5 Cu, may meet the requirements for lead wire. This alloy has 97 percent IACS conductivity and a strength of 32,000 psi in the annealed temper. No information was located regarding its corrosion and oxidation resistance. Based on its high conductivity and high strength, the Ag-1.5 Cu alloy was selected for complete evaluation, in compliance with lead-wire requirements, during this research program.

Other commercial silver-base alloys containing 7.5, 10, 20, or 28 percent copper have borderline conductivity, 86 to 89 percent IACS, and higher annealed strengths, to

54, 000 psi, than the Ag-1.5 Cu composition. However, the possible shortcomings of the Ag-1.5 Cu alloy such as inadequate corrosion and oxidation resistance would be accentuated by the higher copper contents. Thus, these higher copper alloys were not of interest for new slip-ring lead wires.

A list of the companies contacted in the survey of commercial silver alloys and a summary of the data collected on the Ag-1.5 Cu composition are given in Appendix A.

Survey of Alloying Effects

That only one commercial silver alloy appeared capable of meeting the requirements for slip-ring lead wires emphasized that silver alloys have not been developed to meet property requirements similar to those for lead wires. Thus development of new silver alloys specifically for slip-ring lead wires appeared necessary. To aid in the development of new silver-base alloys, the technical literature was searched for information on the effects of alloy elements on the electrical conductivity and tensile strength of silver. Information obtained from the survey is given in Appendix B. Analysis of the alloying effects, leading to the design of 30 compositions as candidate lead-wire alloys is summarized briefly below. A more thorough discussion of the alloying effects of various elements in silver is given in Appendix B.

The effects on the electrical resistivity and strength of silver produced by additions of the various solid-solution elements are summarized in the resistivity-strength plot of Figure 1. Copper, as shown in Figure 1, was found to be decidedly the most effective strengthener commensurate with minimal increase in electrical resistivity.

The maximum content of the solid-solution elements that can be added to silver without lowering the electrical conductivity below 90 percent IACS and the minimum content of alloy to achieve 30, 000-psi tensile strength for the annealed condition are given in Table 2. Among the systems listed in Table 2, only the silver-copper alloys containing between 1.5 and 5 percent copper would be expected to have at least 90 percent IACS conductivity and 30, 000-psi ultimate strength in the annealed condition.

On the other hand, palladium and gold are potentially useful additions for development of a new lead-wire material since these elements, next to copper, are the most effective strengtheners of silver relative to their lowering of electrical conductivity. Alloys of silver with palladium or gold were of particular interest since they were expected to have better corrosion resistance than silver-copper alloys. An ultimate tensile strength of 30, 000 psi might be achieved in dilute silver-palladium and silver-gold alloys by work hardening. Retention of 30, 000-psi strength, during heating of wires for curing Teflon insulation, appeared possible in the binary silver-palladium or silver-gold alloys. If not, their resistance to softening at elevated temperatures was expected to be raised by addition of an insoluble element.

Platinum was also expected to be a useful alloying addition, since up to at least 0.6 percent can be alloyed without lowering conductivity to less than 90 percent IACS. No data on its strengthening potential were located.

The addition of insoluble elements to silver produces alloys with a relatively pure silver matrix containing a dispersion of either the alloy metal or an intermetallic compound. The dispersion-type alloy appeared attractive for slip-ring lead wires

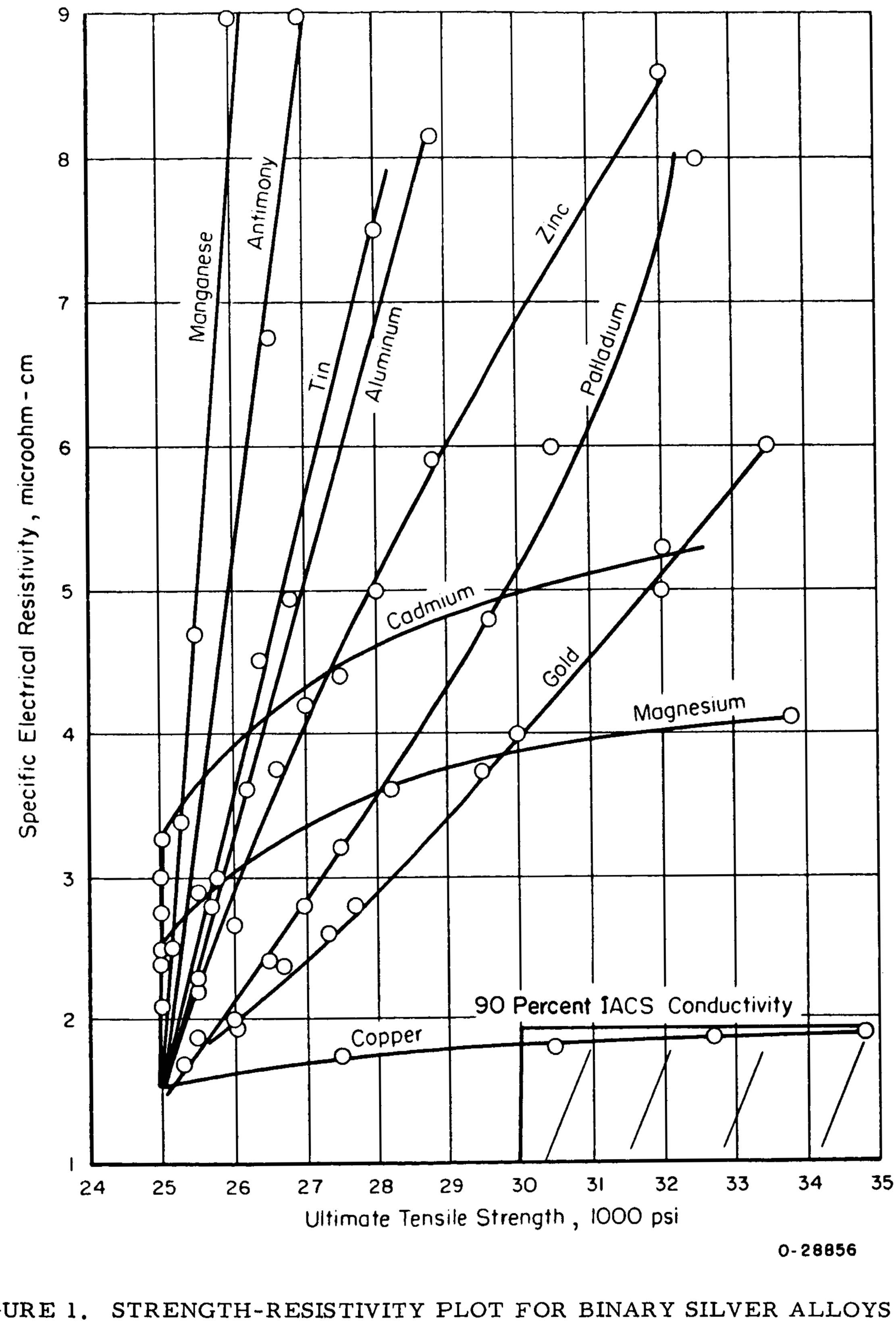

FIGURE 1. STRENGTH-RESISTIVITY PLOT FOR BINARY SILVER ALLOYS CONTAINING SOLID-SOLUTION ELEMENTS (ANNEALED CONDITION)

since its electrical conductivity could be near 100 percent IACS. Furthermore, the ability of dispersion-type alloys to resist softening during application of heat meant that these alloys, in the slightly cold worked condition might not lose strength during curing of Teflon insulation or as a result of soldering.

TABLE 2. LIMITING CONTENTS OF SOLID-SOLUTION ALLOY ELEMENTS IN SILVER FOR 90 PERCENT IACS CONDUCTIVITY AND 30,000-PSI TENSILE STRENGTH

Element	Maximum Content for 90 Percent IACS Electrical Conductivity, weight percent	Minimum Content for 30,000-psi Ultimate Tensile Strength in the Annealed Temper, weight percent
Copper	5	1.5
Palladium	1	9
Gold	1.5	10
Zinc	0.3	7
Aluminum	0.05	1.5
Tin	0.3	3.3
Antimony	0.03	2.5
Manganese	0.1	6.7
Magnesium	0.4	5.1
Cadmium	0.75	15.5
Germanium	0.3	--
Platinum	0.6	--
Indium	0.2	--

The requirements of slip-ring lead wire were expected to be met in dilute, dispersion-type silver alloys by cold working the alloys to achieve 30,000-psi ultimate strength. Data in Table 3 show the effects of cold work on the properties of pure silver and of dispersion-type alloys containing nickel. As shown in Table 3, 30,000-psi strength can be exceeded by as little as 30 percent cold work for a silver alloy containing only 0.1 percent nickel. Also, the electrical conductivity of these wrought silver-nickel alloys is 96 percent IACS. An additional possible advantage of the cold-worked condition for application as lead wires is the greatly improved yield strength. As shown in Table 3, an increase of more than 20,000 psi in yield strength is achieved by only 30 percent cold work.

Based on the effects shown in Table 3, nickel was a promising dispersion-type addition to silver. Titanium, chromium, and beryllium were also of interest as dispersion additions to silver lead-wire alloys since they are very effective in raising the softening temperature of silver. Titanium and beryllium also increase the hardness and probably the strength of silver. Although the effect of these elements on the electrical properties of silver was unknown, they were not expected to significantly lower the conductivity.

Zirconium was also of interest as a dispersion addition to silver on the basis that a high-conductivity dispersion alloy containing Cu-0.3 Zr has outstanding rupture strength and resistance to softening at elevated temperatures.

TABLE 3. EFFECT OF COLD WORK ON THE PROPERTIES OF SILVER AND DILUTE SILVER-NICKEL ALLOYS

Alloy Composition, weight percent	Ultimate Tensile Strength, 1000 psi		Yield Strength, 1000 psi		Elongation, percent in 2 inches		Electrical Conductivity, percent IACS	
	Annealed	Cold Worked	Annealed	Cold Worked	Annealed	Cold Worked	Annealed	Cold Worked
Ag[(a)]	20.9	29.8	4.3	28.7	48	7	102	102
Ag-0.1 Ni[(a)]	23.2	34.7	11.8	32.4	26	4	96	96
Ag-0.6 Ni[(b)]	26.7	43.5	8.8	41.0	42	6	100	96

(a) Cold worked 30 percent reduction in area.
(b) Cold worked 50 percent reduction in area.

Reference: Addicks, L., Silver in Industry, Reinhold Publishing Corporation, New York (1940).

Ruthenium was an interesting dispersion ingredient, since it was reported to increase the electrical conductivity of silver. If this increase is real, ruthenium may be useful in ternary silver alloys to equalize the detrimental effect on conductivity of an element such as aluminum, added to increase the strength. Possibly, the combination of 90 percent IACS conductivity and 30,000-psi ultimate strength could be achieved in the annealed temper in solid-solution alloys containing ruthenium.

Addition of a third element to the silver-copper alloy base appeared useful to obtain improved lead-wire properties compared with those possible in the binary silver-copper alloys. For example, nickel additions to the silver-copper alloys offered the possibility of meeting the requirements of slip-ring lead wires using less copper than 1.5 percent. Reduction of the copper content may be desirable if surface oxidation or lack of corrosion resistance of high-copper areas in silver-copper alloys proves to be a problem. Aluminum is known to reduce the surface oxidation of some alloys. Thus a ternary silver-copper-aluminum alloy might be expected to have improved oxidation resistance compared with the binary silver-copper alloys.

Compositions Selected for Study

An analysis of the available information permitted the selection of 30 silver-alloy compositions that might meet the service requirements in either the annealed or partially worked temper. These compositions are listed in Table 4. The alloys are grouped according to type, as solid-solution alloys, dispersion alloys, or more complex ternary alloys. The latter group contains both solid-solution and dispersion additions.

EXPERIMENTAL PROCEDURES

The basic approach to this program was to examine the effects of alloy additions, annealing treatments, and cold work on the properties of silver-alloy wires. Based on the results of these studies, the three alloys having the best lead-wire properties were selected along with pure silver for scale-up and fabrication to Teflon-insulated, 19-strand, 42-gage lead wires. Procedures used in this work are described below.

TABLE 4. COMPOSITIONS OF SILVER ALLOYS SELECTED FOR EVALUATION

Alloy	Solid-Solution Alloys, weight percent	Alloy	Dispersion Alloys, weight percent	Alloy	Ternary Alloys, weight percent
1	Ag-1 Cu	11	Ag-0.1 Ni	26	Ag-1 Cu-0.1 Ni
2	Ag-1.5 Cu	12	Ag-0.2 Ni	27	Ag-1 Cu-0.2 Ni
3	Ag-3 Cu	13	Ag-0.5 Ni		
4	Ag-5 Cu			28	Ag-1.5 Cu-0.1 Ni
		14	Ag-0.1 Cr	29	Ag-1.5 Cu-0.2 Ni
5	Ag-0.5 Pd	15	Ag-0.2 Cr		
6	Ag-1.0 Pd	16	Ag-0.5 Cr	30	Ag-1 Cu-0.05 Al
7	Ag-1 Au	17	Ag-0.05 Ti		
8	Ag-1.5 Au	18	Ag-0.1 Ti		
		19	Ag-0.3 Ti		
9	Ag-0.6 Pt				
10	Ag-1.5 Pt	20	Ag-0.05 Zr		
		21	Ag-0.1 Zr		
		22	Ag-0.1 Be		
		23	Ag-0.2 Be		
		24	Ag-1 Ru		
		25	Ag-2 Ru		

(a) One percent copper was inadvertently added to Alloy 23 during melting when a copper rod was used to remove slag from the melt surface.

Laboratory Preparation of Alloy Wire

The silver alloys prepared during this program were made from 99.99 fine silver and high-purity alloy elements. Alloying of the metals was accomplished by melting them in an alumina crucible using induction heating. The molten alloys were cast into a copper mold to form cylindrical, 100-gram ingots having a diameter of 1/2 inch and a length of 3 inches.

Entrapped oxygen evolved from the molten silver alloys during solidification produced porosity in the first ingots cast. Although molten silver can absorb about 200 cc of oxygen per 100 grams of metal, only about 10 cc of the oxygen per 100 grams can be retained by solid silver.

In commercial practice, molten silver alloys are often deoxidized with phosphorus or lithium additions. These additions form low-density oxides, which can be removed from the melt surface. However, such practice leaves residual amounts of phosphorus or lithium in the alloys. On the other hand, hydrogen can be used to remove oxygen from silver without being retained in significant amounts. Since this research was concerned with the effects of dilute alloy additions on the properties of silver, hydrogen deoxidation was selected to avoid altering the effects of intentional alloy additions that might result from residual phosphorus or lithium.

Hydrogen deoxidation was accomplished by melting pure silver under a cover of purified hydrogen and by simultaneously bubbling hydrogen through the molten silver. After deoxidation of the silver base, the alloy elements were added through the hydrogen cover and the melt was stirred to achieve homogeneity. Alloys 17-21, containing titanium or zirconium, were not alloyed under a hydrogen cover because these elements form compounds with hydrogen. Rather, the silver base was deoxidized with bubbling hydrogen as with the previous procedure, but argon rather than hydrogen was used to cover the melt. The reactive elements were then added to the deoxidized silver through the argon cover. During the first attempts to make Alloys 17-21, refractory oxide coatings formed on the reactive metals while they floated on the melt surface. These oxide coatings prevented the titanium and zirconium additions from dissolving in the silver. Oxidation of these reactive additions was subsequently prevented by wrapping them in silver foil. Alloying of the wrapped additions was achieved by plunging them under the surface of the molten silver and by holding them in the melt for sufficient time to dissolve the titanium and zirconium.

The 100-gram ingots of the experimental silver alloys were fabricated to 0.050-inch-diameter wire for preliminary evaluations. Selected compositions were later drawn to 0.010- and 0.0027-inch diameters for more extensive study.

All the silver ingots were machined over the circumference to remove surface contamination before they were fabricated. The machined ingots were swaged at room temperature from about 0.450-inch diameter to 0.204-inch diameter. They were then drawn to 0.152-inch diameter using reductions of one B & S number per pass. All rods were annealed at 0.152-inch diameter. Subsequent fabrication of the annealed rods to 0.050-inch diameter was conducted over several routes to obtain wire specimens with different amounts of room-temperature work. These fabrication routes are illustrated in Figure 2, and a list of the amount of work in specimens of the various silver alloys is given in Table 5.

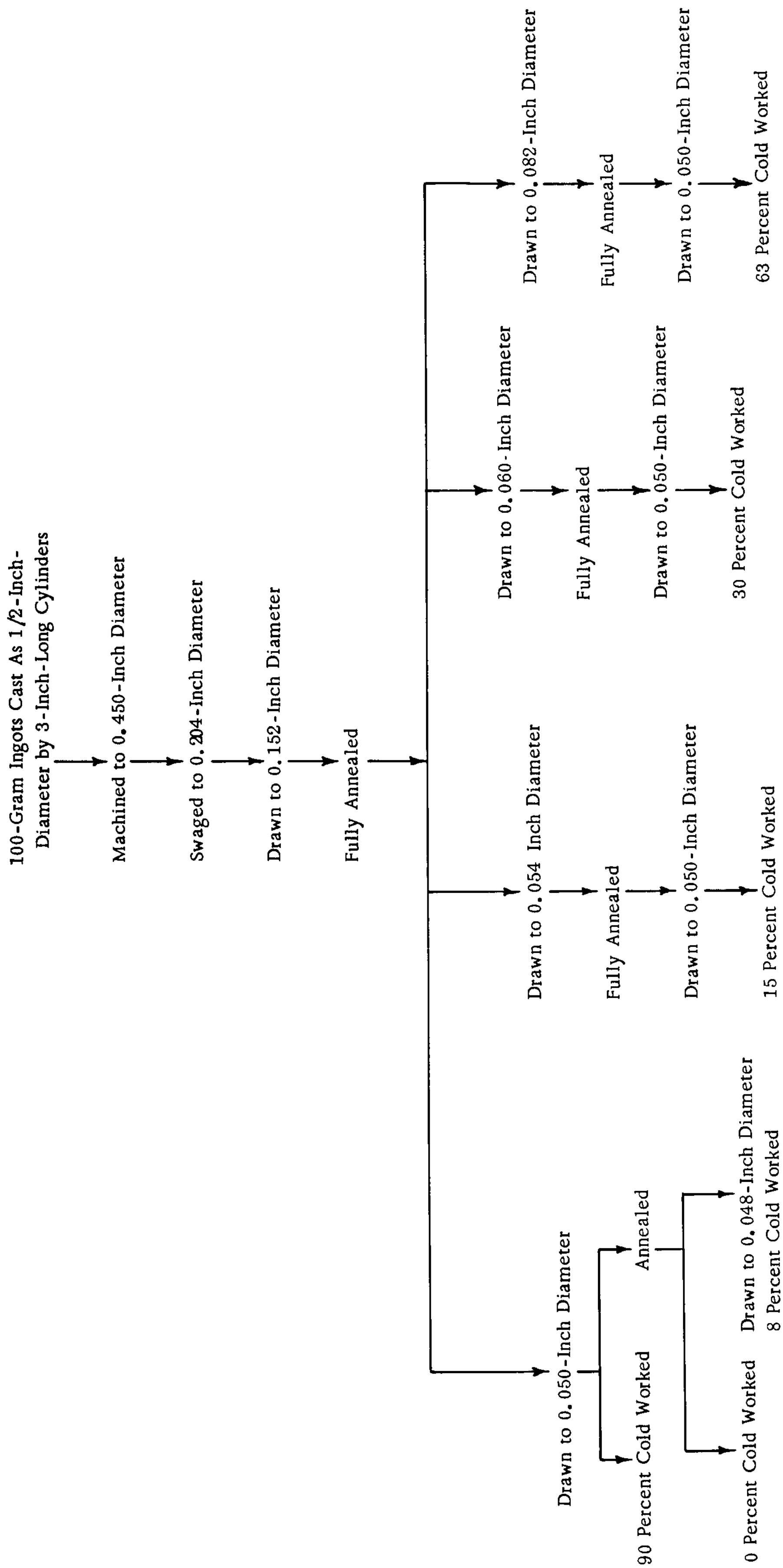

FIGURE 2. FABRICATION SCHEDULE FOR 0.048-, 0.050-INCH-DIAMETER WIRES

TABLE 5. CONDITIONS OF WORK OF ALLOY WIRES PRODUCED DURING THIS PROGRAM

Alloy	Composition, weight percent	Amounts of Room-Temperature Work After Being Annealed, percent reduction in area					
		0(b)	8(a)	15(b)	30(b)	63(b)	90(b)
0	Ag	x		x	x	x	x
1	Ag-1 Cu	x			x	x	x
2	Ag-1.5 Cu	x			x	x	x
3	Ag-3 Cu	x	x		x		x
4	Ag-5 Cu	x			x	x	x
5	Ag-0.5 Pd	x			x	x	x
6	Ag-1 Pd	x			x	x	x
7	Ag-1 Au	x			x	x	x
8	Ag-1.5 Au	x			x	x	x
9	Ag-0.6 Pt	x			x	x	x
10	Ag-1.5 Pt	x			x	x	x
11	Ag-0.1 Ni	x			x	x	x
12	Ag-0.2 Ni	x			x	x	x
13	Ag-0.5 Ni	x		x	x		
14	Ag-0.1 Cr	x			x	x	x
15	Ag-0.2 Cr	x	x		x		x
16	Ag-0.5 Cr	x		x	x		
17	Ag-0.05 Ti	x		x	x		
18	Ag-0.1 Ti	x		x	x		
19	Ag-0.3 Ti	x		x	x		
20	Ag-0.05 Zr	x		x	x		
21	Ag-0.1 Zr	x		x	x		
22	Ag-0.1 Be	x		x	x		
23	Ag-1 Cu-0.2 Be	x		x	x		
24	Ag-1 Ru	x		x	x		
25	Ag-2 Ru	x		x	x		
26	Ag-1 Cu-0.1 Ni	x	x		x		x
27	Ag-1 Cu-0.2 Ni	x			x	x	x
28	Ag-1.5 Cu-0.1 Ni	x	x		x		x
29	Ag-1.5 Cu-0.2 Ni	x	x		x		x
30	Ag-1 Cu-0.1 Al	x			x	x	x

(a) Diameter of wires with 8 percent work was 0.048 inch.
(b) Diameter of wires with 0, 15, 30, 63, or 90 percent work was 0.050 inch.

The 0.010- and 0.0027-inch-diameter wires of selected alloys were drawn from the 0.050-inch-diameter wires in the annealed temper. No intermediate annealing treatments were required to draw the wires from 0.050- to 0.0027-inch diameter.

All wire specimens annealed during fabrication were sealed in Vycor tubes under a partial pressure of argon to prevent them from oxidizing. The 0.050-inch-diameter wires were also protected in argon-filled capsules during the final annealing treatments. All specimens were allowed to cool to room temperature in their protective tubes.

To produce the effects on wire properties that will result from the thermal cycle used to cure Teflon insulation on lead wires, specimens of all the alloy wires in both a worked condition and an annealed condition were heated in air for 2 minutes at 700 F.

Evaluation Procedures

Tensile Tests

Tensile properties were measured on wire specimens using an Instron tensile test machine. Ultimate and 0.2 percent offset yield strengths were calculated from load values taken from the load-time curves recorded during each test. These elongation values represent the distance the specimen holding jaws moved apart during the time between the initial application of the load and the fracture of specimens. Since neither slipping nor necking of the specimens occurred in the holding jaws, these elongation values are an accurate measurement of the total specimen elongation.

Prior to the tensile testing of experimental alloys, the effects of strain rate and specimen gage length on the tensile properties of pure silver and the commercial alloy, Consil 950 (Ag-5 Cu)*, were investigated. This investigation showed that the ultimate and yield strengths of silver are not significantly affected by strain rates in the range of 0.0025 in./in./min to 0.125 in./in./min or by specimen gage lengths in the range of 2 to 4 inches. Likewise, the reduction in area is also unaffected by strain rate and gage length. On the other hand, the elongation of worked silver is nearly independent of the test rate, but is an inverse function of the specimen gage length.

Results of the investigation of strain rate and specimen gage length effects on the tensile properties of pure silver and the commercial Ag-5 Cu alloy are given in Table 6.

A strain rate of 0.125 in./in./min was selected for initial tensile tests on the experimental alloys. However, the strain rate was changed after several tests to 0.05 in./in./min to increase the testing time to at least 30 seconds as recommended by the American Society for Testing and Materials. The gage lengths used for testing laboratory-processed wires were either 2 or 4 inches depending on the length of wire available.

Tensile tests on commercially produced wire of the scaled-up alloys and of silver-plated copper were conducted with a strain rate of 0.1 in./in./min using a 10-inch gage length.

*This sample of Consil 950 (Ag-5 Cu) was supplied by Handy and Harman Company.

TABLE 6. EFFECTS OF STRAIN RATES AND SPECIMEN GAGE LENGTHS ON THE TENSILE PROPERTIES OF PURE SILVER AND Ag-5 Cu

All wires were worked at room temperature 30 percent RA prior to testing.

Strain Rate, in./in./min	Gage Length, inches	0.2 Percent Offset Yield Strength, ksi	Ultimate Strength, ksi	Elongation, per cent	Reduction in Area, percent
		Pure Silver			
0.125	4	37.7	37.9	3.8	98.6
0.125	2	36.7	37.2	11.8	94.0
0.100	2	36.2	37.4	7.0	94.0
0.0025	4	36.2	37.2	3.5	94.5
		Ag-5 Cu			
0.125	4	51.8	56.0	2.5	85.2
0.05	4	50.9	55.5	2.5	85.3

Electrical-Conductivity Measurements

The electrical conductivities of the experimental alloys were calculated from measurements of the voltage drop produced by a measured current flowing through the wire specimen. Voltage drops were measured for each alloy specimen at three current levels. Temperatures of the wires were kept at 72 F during the conductivity measurements.

Flexure-Breakage Tests

The resistance of wire specimens to flexure breakage was determined on a device designed and constructed at Battelle. Sketches of this apparatus are shown in Figure 3.

In operation, the flexure-breakage machine bends wire specimens through an angle of 95 degrees over a selected radius of 0.025, 0.05, or 0.1 inch. Tests were conducted at a bend rate of 6 cycles per minute (a cycle consists of a bend through 95 degrees and return to 0 degrees). Tensile loads of various magnitudes were applied to specimens during the tests by hanging a weight on the free end of the wire. The number of bend cycles required to break specimens of laboratory-processed wire were counted by using an electrical circuit in which the wire specimens were in series with electrical counters. Upon failure of a specimen, an open circuit would result stopping the associated counter.

Flexure-breakage tests on 19-strand wire of the scaled-up alloys were also conducted on the Battelle bend device. During these tests the electrical resistance of the specimens was monitored using the circuit shown in Figure 4.

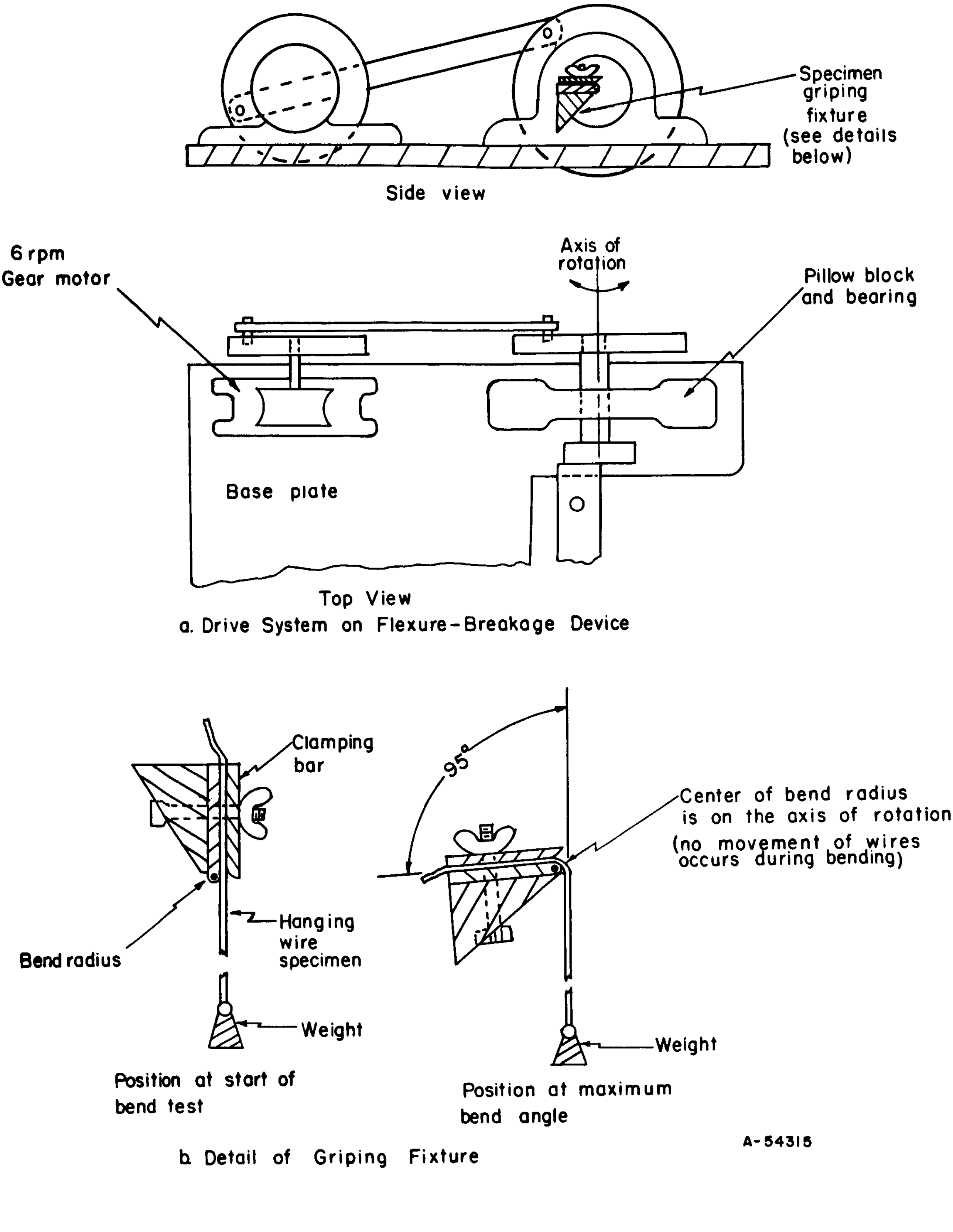

FIGURE 3. SKETCHES OF THE FLEXURE-BREAKAGE DEVICE USED DURING THIS STUDY

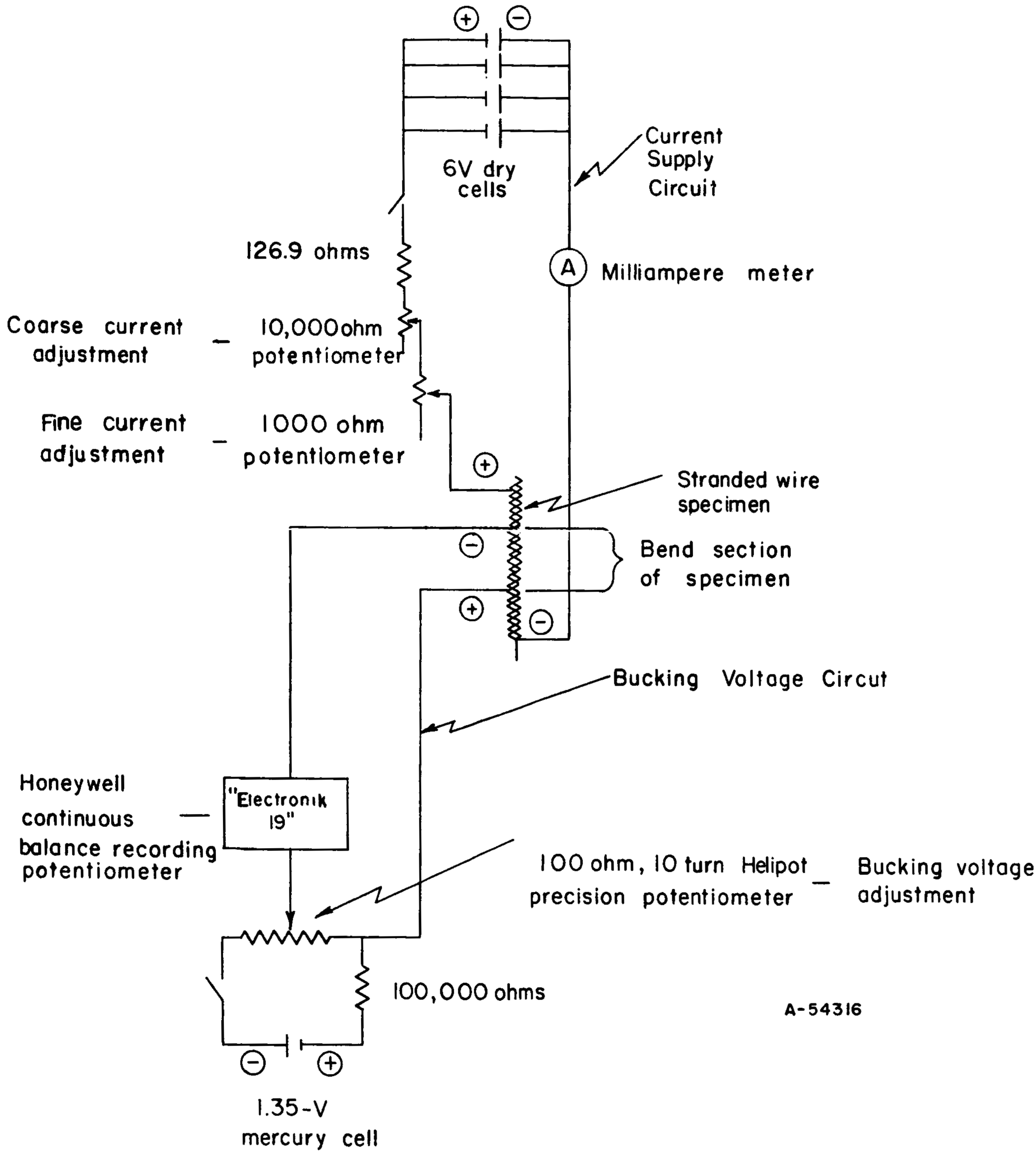

FIGURE 4. ELECTRICAL CIRCUITS USED FOR MONITORING ELECTRICAL RESISTANCE OF STRANDED SPECIMENS DURING BEND TESTS

In operation, a constant direct current of 15 milliamperes was passed through the specimens. The voltage drop produced by this current across the bend section was opposed by a variable constant-voltage source as shown in Figure 4. This "bucking-voltage" was adjusted to allow only 0.02 millivolts of the actual voltage drop across the bend section to reach the recording potentiometer. As a result, the voltage drop could be monitored on the most sensitive range of the potentiometer. A change in the voltage drop, across a bend specimen, of 0.5×10^{-6} volt (3×10^{-6} ohm resistance change) could be detected.

Rupture of strands during the tests was revealed by a sharp increase in the electrical resistance. While failure of first strands, in the cables tested with insulation, could be detected by the resistance change, failure of the 19th strand could not be detected.

Corrosion Tests

The corrosion resistance of selected alloys was evaluated on 0.050-inch-diameter wires in both cold-worked and annealed conditions. These specimens were alternately immersed in a room-temperature solution of water:2 percent hydrofluoric acid:5 percent sodium fluoride using 10 minutes in solution, 50 minutes out per hour. This corrosion test was expected to accelerate any corrosion tendency the alloys might have in the form of Teflon-insulated lead wires.

Each week during the tests, the wire specimens were removed from the corrosion solution, cleaned, and weighed to detect loss of material as corrosion products. Also on a weekly basis, specimens were examined under a microscope for visual evidence of corrosion.

RESULTS OF STUDIES OF LABORATORY-PROCESSED WIRE

Evaluation of the experimental alloys was based on two approaches to achieve an improved slip-ring lead wire. Some of the silver alloys, particularly those containing copper, were expected to have a strength of 30,000 psi or greater combined with an electrical conductivity of at least 90 percent IACS in the annealed condition. Most of the alloys, however, were not expected to have strengths as high as 30,000 psi in the annealed temper, but were expected to be strengthened to 30,000 psi by slight cold work. High softening resistance, imparted by some of the alloy additions, was expected to prevent this worked strength from being lost during the 700 F Teflon-curing cycle.

Strength and electrical-conductivity measurements were made on all the alloys in both the annealed and cold-worked conditions. Selected alloys that met the NASA requirements of 30,000-psi strength and 90 percent IACS conductivity in either of these conditions were studied further. These follow-through studies included determination of the flexure-breakage resistance, corrosion resistance, oxidation resistance, solderability, and fabricability to 41-gage wire.

The results of these studies are summarized in this section of the report. A complete tabulation of the experimental data on laboratory-processed wire is given in Appendix C.

Annealing Studies

To determine the temperatures required to fully anneal the silver alloys, specimens in the 90 percent worked condition were heated for 1 hour at each of the temperatures 400, 600, 800, 1000, 1200, and 1400 F. The lowest temperatures that produced the fully annealed structure in the alloys in 1 hour are given in Table 7. Those temperatures were used in subsequent studies to produce alloys in the fully annealed condition.

Softening resistance of cold-worked alloys was determined from hardness measurements on the specimens annealed at the various temperatures. Also given in Table 7 are the temperatures at which the alloys softened to a hardness, $H_{1/2}$, midway between their hardnesses in the 90 percent worked and the fully annealed conditions. Increased resistance to softening is reflected by high temperatures corresponding to the hardness, $H_{1/2}$. The average hardness values, as a function of 1-hour annealing temperatures, are given in Appendix C, Table C-1.

As shown in Table 7, at least 17 of the silver alloys had greater resistance to softening during heating than pure silver. Many of these alloys would be expected to retain cold-worked strengths after the 700 F exposure used to cure Teflon insulation. Consequently, those 17 alloys offered the possibility of usefulness as lead wires in the worked condition to achieve strengths of at least 30,000 psi.

Data in Table 7 also show that the alloys containing copper had the highest softening temperatures among the compositions studied. Interestingly, the effectiveness of copper in raising the softening temperature is increased by nickel additions. For example, the addition of 0.2 Ni to the Ag-1.5 Cu alloy raised the softening temperature 80 F, while 0.2 Ni raised the softening temperature of the Ag-1 Cu alloy 130 F. As shown in Table 7, the ternary Ag-Cu-Ni alloys at the 1 and 1.5 percent copper levels had softening temperatures second only to the Ag-3 Cu alloy.

The alloys containing the dispersion elements, 0.1 Zr, 0.3 Ti, 0.1 or 0.2 Ni also had softening temperatures significantly above the softening temperature of pure silver. On the other hand, the dispersion elements chromium, beryllium, and ruthenium did not noticeably increase the softening temperature of pure silver.

The solid-solution alloys containing 1 Pd or 1.5 Pt had slightly improved softening resistance. Other solid-solution alloys with lesser amounts of palladium or platinum than 1 or 1.5 percent, respectively, or with gold, apparently had no better softening resistance than pure silver.

Properties of Experimental Alloys in the Annealed Condition

The ultimate tensile strengths and electrical conductivities of pure silver and 28 of the experimental silver alloys, in the fully annealed condition, are shown in Figure 5. A complete tabulation of the data used in preparing this figure is given in Appendix C, Table C-2. Alloy 24 (Ag-1 Ru) was not evaluated in the annealed condition because a chemical analysis revealed the alloy contained less than 0.05 percent ruthenium. Tensile properties of Alloy 30 (Ag-1 Cu-0.1 Al) were not evaluated for the annealed condition, since its electrical conductivity in the annealed condition was very low, about

TABLE 7. RESULTS OF ANNEALING STUDIES ON PURE SILVER AND THE EXPERIMENTAL ALLOYS

Alloy	Composition, weight percent	Annealing Temperature to Produce a Fine-Grained Equiaxed Structure in 1 Hour, F	Temperature to Lower the Hardness of 0.050-Inch-Diameter Wire to a Value, $H_{1/2}$, Midway Between the Hardness of the 90 Percent Worked and Fully Annealed Conditions, F
0	Ag	800	<400
1	Ag-1 Cu	1000	580
2	Ag-1.5 Cu	1000	640
3	Ag-3.0 Cu	1200	740
4	Ag-5 Cu	1400	590
5	Ag-0.5 Pd	1200	<400
6	Ag-1 Pd	1200	490
7	Ag-1 Au	800	<400
8	Ag-1.5 Au	800	<400
9	Ag-0.6 Pt	1200	<400
10	Ag-1.5 Pt	1200	470
11	Ag-0.1 Ni	1400	490
12	Ag-0.2 Ni	1400	470
13	Ag-0.5 Ni	1400	500
14	Ag-0.1 Cr	1400	<400
15	Ag-0.2 Cr	1400	<400
16	Ag-0.5 Cr	1400	<400
17	Ag-0.05 Ti	1200	<400
18	Ag-0.1 Ti	1200	<400
19	Ag-0.3 Ti	1200	540
20	Ag-0.05 Zr	1200	<400
21	Ag-0.1 Zr	1200	610
22	Ag-0.1 Be	1200	<400
23	Ag-1 Cu-0.2 Be	1200	600
24	Ag-1 Ru	1400	<400
25	Ag-2 Ru	1400	<400
26	Ag-1 Cu-0.1 Ni	1200	690
27	Ag-1 Cu-0.2 Ni	1200	710
28	Ag-1.5 Cu-0.1 Ni	1200	720
29	Ag-1.5 Cu-0.2 Ni	1400	720
30	Ag-1 Cu-0.1 Al	1200	650

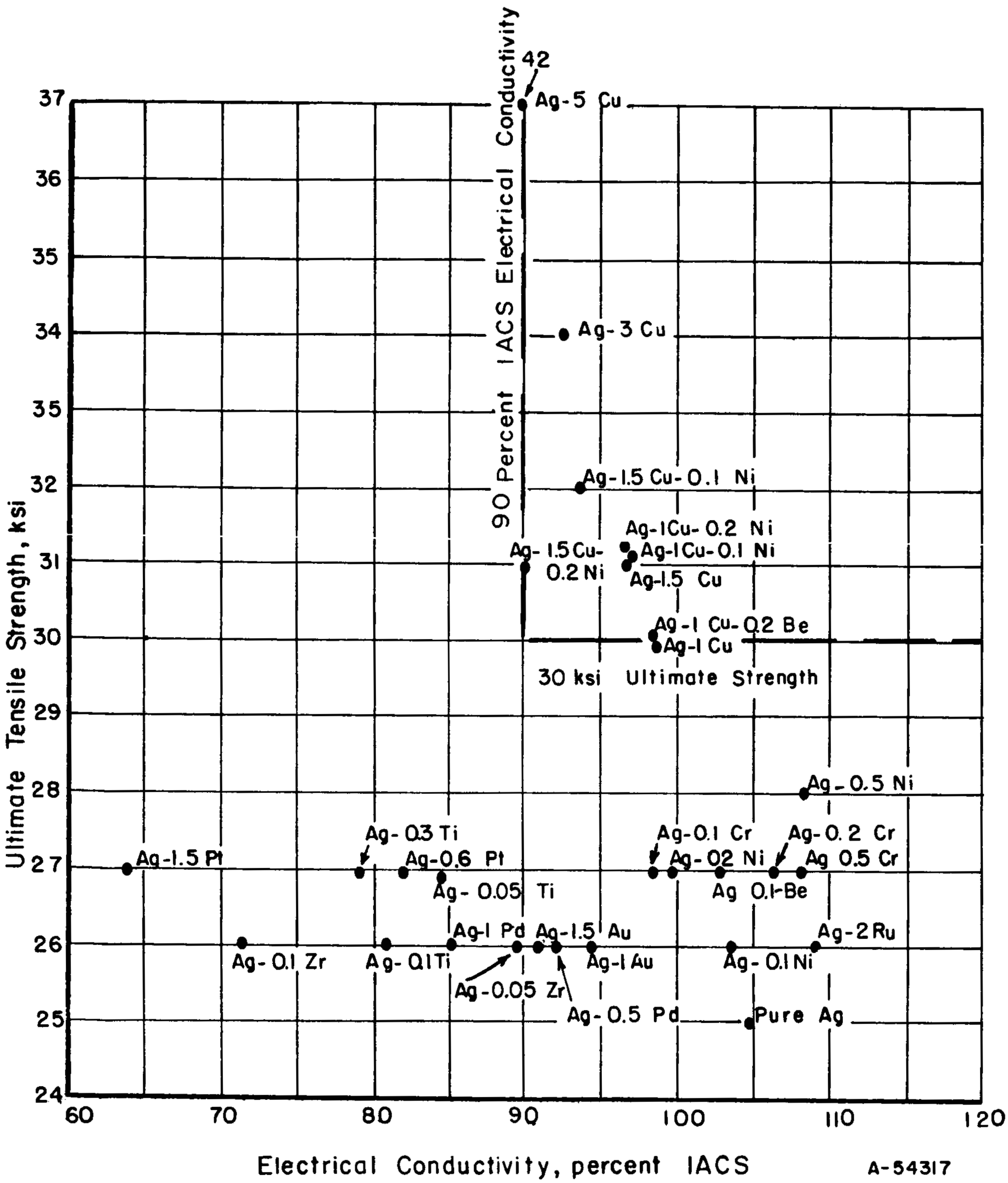

FIGURE 5. STRENGTH:CONDUCTIVITY PROPERTIES OF EXPERIMENTAL SILVER ALLOYS IN THE ANNEALED CONDITION

58 percent IACS. As shown in Figure 5, only eight of the alloys were capable of meeting the NASA strength-conductivity requirements in the annealed condition. All of these alloys contained at least 1 percent copper. While the Ag-5 Cu alloy had a strength exceeding 30,000 psi, its electrical conductivity was slightly below 90 percent IACS.

Twelve of the alloys and pure silver had electrical conductivities above 90 percent IACS but had strengths below 30,000 psi in the annealed condition. Alloys in this category could possibly meet lead-wire requirements in a worked condition to achieve the 30,000-psi strength.

Eight alloys had strengths below 30,000 psi and electrical conductivities below 90 percent IACS. These alloys were not of interest for lead wires in the wrought condition since cold work would further lower their conductivity.

As reported in the literature, ruthenium did slightly increase the electrical conductivity of pure silver. Chromium additions in amounts of 0.2 and 0.5 percent also slightly increased the conductivity but to a lesser extent than ruthenium. However, neither ruthenium nor chromium appeared to raise the conductivity enough to make them useful ternary additions for equalizing the lowering of conductivity by very effective solid-solution strengtheners such as aluminum.

All of the annealed silver alloys were very ductile with elongations ranging from 31 to 53 percent and reductions in area ranging from 44 to 97 percent.

Properties of Experimental Alloys in Cold-Worked Conditions

Cold working of the silver alloys with 90 percent conductivity and with strengths below 30,000 psi in the annealed condition was studied as a method of increasing alloy strengths to the minimum of 30,000 psi. The alloys containing copper that met lead-wire requirements in the annealed condition were also cold worked to investigate the possibility that these alloys might have better properties for lead wires in the worked condition than in the annealed condition. The effects of room-temperature deformation on the ultimate strengths and elongations of the silver alloys are summarized in Figure 6. Data used in preparing this figure are given in Appendix C, Table C-3.

Two patterns of strengthening from cold work are apparent for the silver alloys. The upper strength band in Figure 6 includes the strengths of the alloys containing copper. The lower strength band includes the strengths of the copper-free silver alloys. The upper strength line for the alloys with copper shows the variation of ultimate strength with cold work for the most highly alloyed composition, Ag-5 Cu. This curve shows that the strength of the annealed Ag-5 Cu alloy can be increased about 36,000 psi by 90 percent deformation. The lower line of the band for the copper containing alloys shows the increase in strength of the most dilute alloy with copper, Ag-1 Cu, is about 33,000 psi for 90 percent work. Thus, the strengthening response to cold work of the alloys containing copper, is relatively independent of the copper content. However, the alloys containing both copper and nickel, which have strengths within the band, showed slightly greater strengthening response to cold work than the binary copper alloys. As much as 44,000-psi increase in strength was produced in the Ag-1.5 Cu-0.2 Ni composition by 90 percent work.

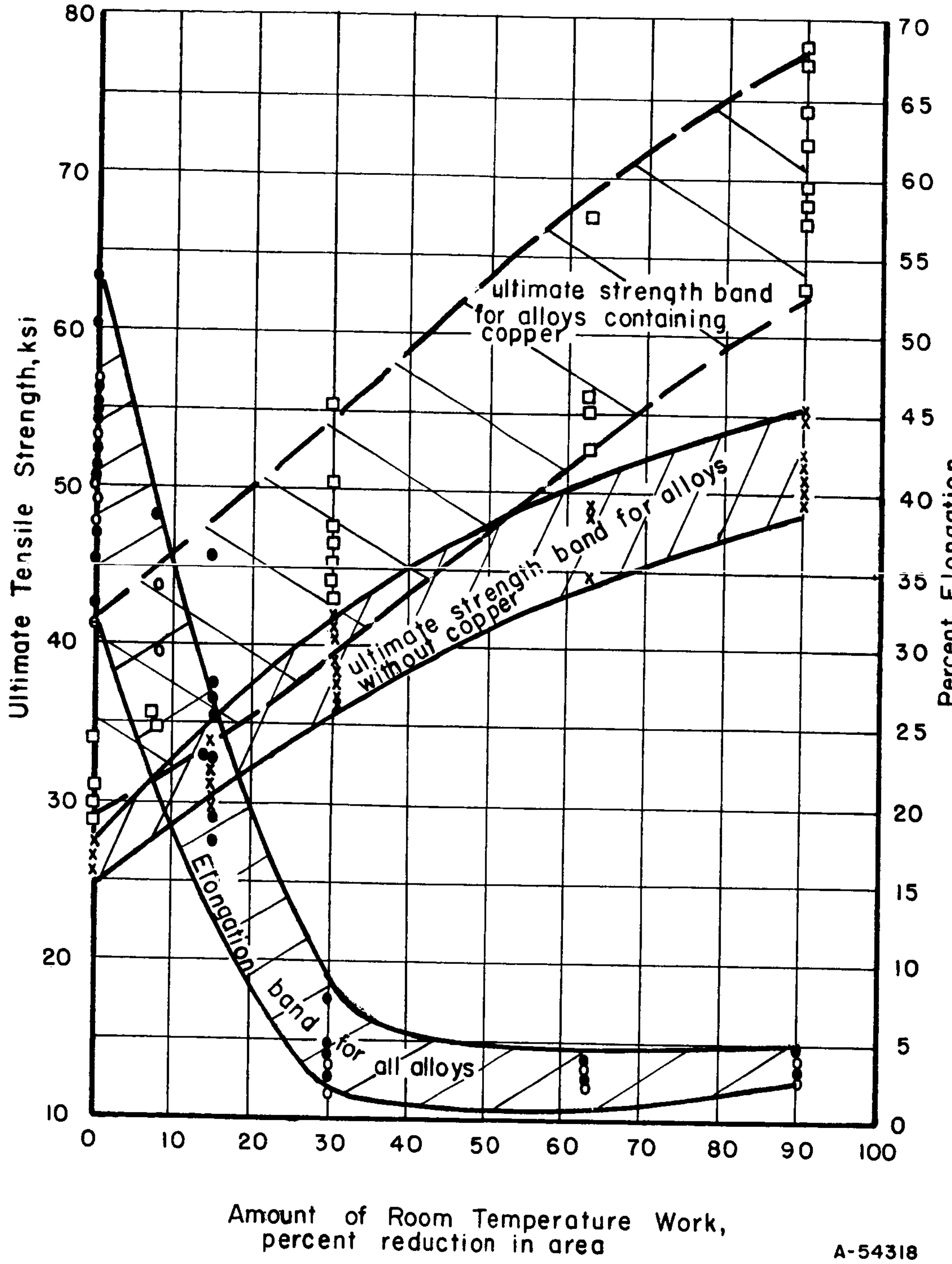

FIGURE 6. EFFECT OF COLD WORK ON THE STRENGTH AND DUCTILITY OF EXPERIMENTAL SILVER ALLOYS

The strength band for all the alloys without copper is displaced to lower strength levels than the band for alloys containing copper because the annealed strengths were lower. Also, the silver alloys without copper are slightly less effectively strengthened by cold work. As shown in Figure 6, the median strength increase of the silver alloys without copper is about 26,000 psi for 90 percent cold work. Among the alloys with strengths in the lower band, the compositions containing nickel were most effectively strengthened by cold work. For example, the strength of the Ag-0.1 Ni alloy was increased 29,000 psi by 90 percent deformation.

Strengthening the silver alloys by room-temperature work simultaneously lowered their tensile elongation. Variation of the elongation with amount of work is shown, for all the alloys, by the elongation band in Figure 6. As shown in Figure 6, the tensile elongation of the alloys was lowered to 2 to 8 percent by 30 percent work. With greater amounts of cold work, all the alloys had tensile elongations between 2 and 5 percent. Despite low elongation values, the worked alloys retained good ductility, evidenced by retention of reduction of area values from 74 to 94 percent after 90 percent work. The low elongation conditions resulted from the fact that the alloy test specimens necked sharply in a localized region.

In contrast with the significant changes in tensile strength and elongation produced by room-temperature deformation, the electrical conductivity of all the alloys was little affected. For example, the electrical conductivity of all the alloys was lowered only 5 to 7 percent by 90 percent deformation. The decrease in conductivity varied linearly with degree of work to the extent of about -0.8 percent IACS per 10 percent work. Thus, alloys with 93 percent IACS conductivity could be worked at least 30 percent to increase strength without lowering the electrical conductivity below the NASA requirement of 90 percent IACS. Electrical properties of the wrought alloys are also given in Appendix C, Table C-3.

Overall consideration of the data in Figure 6 shows that the amount of cold work used to strengthen silver alloys for lead wires should be limited to 8 to 20 percent, depending on the specific alloy, to maintain tensile elongations of at least 20 percent. This elongation criteria was based on early speculation that flex life depends on elongation as well as strength; i.e., a good elongation should produce improved flex life. Strengths possible with 8 to 20 percent work would range from 31 to 44 ksi for the alloys containing copper and from 28 to 38 ksi for the alloys without copper. Alloys with at least 92 percent IACS electrical conductivity in the annealed condition would have at least 90 percent IACS conductivity after being worked 8 to 20 percent.

From the effects of cold work on the properties of the silver alloys, combined with consideration of their softening resistance and annealed electrical conductivity, the compositions listed in Table 8 showed potential usefulness as lead wires in the worked condition. As shown in Table 8, these worked alloys are expected to have strengths in the range of 36-44 ksi and electrical conductivities in the range 90-106 percent IACS, at the 20 percent elongation level. Furthermore, the high softening temperatures of the alloys in Table 8 should permit these alloys to retain most of their wrought strength following a Teflon-curing cycle.

TABLE 8. ALLOYS POTENTIALLY USEFUL IN A COLD-WORKED CONDITION

Alloy	Estimated Maximum Amount of Cold Work for 20 Percent Elongation, percent RA	Estimated Strength at 20 Percent Elongation, ksi	Estimated Electrical Conductivity of Alloys Worked to 20 Percent Elongation Level, percent IACS
Ag-1 Cu	18	35	97
Ag-1.5 Cu	18	40	95
Ag-3 Cu	18	44	90
Ag-0.1 Ni	20	36	102
Ag-0.2 Ni	20	38	98
Ag-0.5 Ni	20	38	106
Ag-1 Cu-0.2 Be	15	38	97
Ag-1 Cu-0.1 Ni	15	38	95
Ag-1 Cu-0.2 Ni	15	38	95
Ag-1.5 Cu-0.1 Ni	12	38	92
Ag-1.5 Cu-0.2 Ni	12	39	94

Properties of Cold-Worked Alloys After Exposure at 700 F

From the alloys expected to have at least 30,000-psi strength after being worked and exposed at 700 F to the Teflon-curing cycle, the following compositions were selected for further study:

Ag-1.5 Cu
Ag-0.2 Ni
Ag-1 Cu-0.2 Be
Ag-1 Cu-0.1 Ni
Ag-1 Cu-0.2 Ni
Ag-1.5 Cu-0.1 Ni
Ag-1.5 Cu-0.2 Ni

Also chosen for evaluation in the worked plus 700 F exposed condition were the following alloys which were not expected to retain 30-ksi strength after Teflon curing:

Pure Silver
Ag-0.5 Pd
Ag-0.1 Cr
Ag-0.1 Be

Pure silver was included for baseline data. The alloys offered potentially better corrosion resistance and fabricability than the copper-containing alloys, combined with high electrical conductivities and potential strengths near 30 ksi.

The alloys selected for evaluation after the simulated Teflon-curing cycle were worked at room temperature to strengths above 30 ksi and were subsequently heated for

2 minutes at 700 F in air. This 700 F exposure was expected to lower the worked strength of the alloys at least as much as the actual Teflon-curing cycle.

Average tensile properties of the worked and exposed alloys are given in Table 9. Complete tensile properties of the exposed alloys are given in Appendix C, Table C-4. For comparison purposes, the worked strengths before 700 F exposure and the strengths in the fully annealed condition are also given in Table 9. As shown in Table 9, the wrought strengths of the alloys containing copper were only slightly lowered by the 700 F exposure whether worked to 8, 15, or 30 percent RA by prior drawing. The Ag-1.5 Cu and Ag-1 Cu-0.2 Ni alloys, which were worked to achieve strengths near 40,000 psi after exposure, had low elongation in the worked condition. However, the elongations were improved substantially by the 700 F treatment. The yield strengths of the worked alloys containing copper were lowered by the 700 F exposure slightly more than the ultimate strengths but not enough to produce a strength spread of more than 8,000 psi between the ultimate and yield strengths.

As expected, the worked strengths of pure silver and the Ag-0.5 Pd, Ag-0.1 Cr, Ag-0.1 Be alloys were reduced by the 700 F treatment. In fact their worked strengths were lowered to the strength values for the annealed condition. Consequently, no strength advantage could be gained by working slip-ring lead wires of those materials, since it would be lost during the Teflon-curing cycle.

The Ag-0.2 Ni alloy was not evaluated in the worked and exposed condition because sufficient wire was not available. Rather, Alloy 11 (Ag-0.1 Ni) was evaluated on the basis that the retention of strength in the Ag-0.2 Ni alloy would be at least as good as for the Ag-0.1 Ni composition. As shown in Table 9, the strength of Alloy 11 worked 30 percent and exposed at 700 F was lowered to 27.4 ksi. However, the strength of the Ag-0.2 Ni alloy is expected to be about 2,000 psi greater than for Alloy 11, or about 30 ksi. Therefore, worked Alloy Ag-0.2 Ni has promise of meeting NASA's strength: conductivity requirements after Teflon curing.

Properties of Selected Alloys in a Partially Annealed Condition

Strengths and ductilities intermediate between the values of the worked plus 700 F exposed condition and the values of the fully annealed condition can be achieved in the alloys containing copper by annealing them at 800 F. After 1 hour at 800 F, some of the strength from cold work is retained and the tensile elongations are significantly improved. The 800 F partial anneal is not useful for other alloys among the experimental compositions, since these alloys would not retain strengths above the fully annealed values. Although annealing temperatures on the order of 400-600 F could be used to achieve the partially annealed condition in the alloys without copper, the 700 F Teflon-curing exposure would undoubtedly lower the partial annealed strengths to the fully annealed condition.

The average ultimate strengths and electrical conductivities of the partially annealed alloys containing copper are compared with their average properties in the fully annealed condition in Table 10. All the test results on the partially annealed alloys are given in Appendix C, Table C-5. The ultimate strengths of the partially annealed condition range from 2,000 to 5,000 ksi above the fully annealed strengths. Yield strengths of the partially annealed alloys were about 10,000 psi above the fully annealed levels. These increased strengths in the partially annealed alloys were achieved with

TABLE 9. TENSILE PROPERTIES OF PURE SILVER AND THE SELECTED ALLOYS SHOWING THE EFFECT OF THE SIMULATED TEFLON-CURING TREATMENT ON THE PROPERTIES OF MATERIALS IN THE WORKED CONDITION (AVERAGE VALUES ON TWO SPECIMENS ARE REPORTED)

Alloy	Composition, weight percent	Condition	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation, percent
0	Ag	Worked 30 percent RA	37.4	36.9	7.5[a]
		After 700 F exposure	24.6	7.8	52.3[b]
		Annealed at 800 F	25.4	7.5	46.3[a]
2	Ag-1.5 Cu	Worked 30 percent RA	44.1	42.1	2.6[a]
		After 700 F exposure	39.5	35.2	11.8[a]
		Annealed at 1000 F	30.9	9.5	46.8[a]
5	Ag-0.5 Pd	Worked 30 percent RA	37.5	36.4	3.1[a]
		After 700 F exposure	25.4	8.7	59.0[b]
		Annealed at 1200 F	25.8	6.6	41.1[a]
11	Ag-0.1 Ni	Worked 30 percent RA	41.6	38.2	2.5[a]
		After 700 F exposure	27.4	11.4	43.5[a]
		Annealed at 1400 F	26.3	7.7	40.2[a]
14	Ag-0.1 Cr	Worked 63 percent RA	45.8	42.8	4.0[b]
		After 700 F exposure	26.6	10.7	56.5[b]
		Annealed at 1400 F	26.9	7.4	37.0[a]
22	Ag-0.1 Be	Worked 15 percent RA	32.0	28.5	22.8[a]
		After 700 F exposure	26.9	8.3	41.6[a]
		Annealed at 1200 F	27.4	10.1	45.9[a]
23	Ag-1 Cu-0.2 Be	Worked 15 percent RA	36.1	33.1	17.3[a]
		After 700 F exposure	34.4	28.7	21.6[a]
		Annealed at 1400 F	30.1	9.8	31.6[a]
26	Ag-1 Cu-0.1 Ni	Worked 8 percent RA	33.6	28.9	33.8[a]
		After 700 F exposure	32.8	24.9	32.5[b]
		Annealed at 1200 F	30.5	11.4	40.0[a]
27	Ag-1 Cu-0.2 Ni	Worked 30 percent RA	46.6	41.3	2.6[a]
		After 700 F exposure	40.7	37.4	14.0[b]
		Annealed at 1200 F	30.4	12.1	39.3[a]
28	Ag-1.5 Cu-0.1 Ni	Worked 8 percent RA	34.7	30.0	25.9[a]
		After 700 F exposure	34.3	26.2	29.4[a]
		Annealed at 1200 F	31.8	11.7	38.6[a]
29	Ag-1.5 Cu-0.2 Ni	Worked 8 percent RA	35.8	31.4	24.3[a]
		After 700 F exposure	35.2	27.5	26.8[a]
		Annealed at 1400 F	30.8	9.5	37.2[a]

(a) Gage length was 4 inches.
(b) Gage length was 2 inches.

TABLE 10. PROPERTIES OF SELECTED ALLOYS WITH COPPER IN THE PARTIALLY ANNEALED AND FULLY ANNEALED CONDITIONS

Alloy	Composition, weight percent	Annealed Condition	Annealing Temperature, F(a)	Ultimate Tensile Strength, ksi	0.2 Percent Yield Strength, ksi	Elongation, percent in 4 inches	Electrical Conductivity, percent IACS
2	Ag-1.5 Cu	Partial	800	33.6	19.1	42.6	94.3
		Full	1000	30.9	9.5	46.8	96.6
23	Ag-1 Cu-0.2 Be	Partial	800	31.7	17.6	42.0	98.3
		Full	1400	30.1	9.8	31.6(b)	98.3
26	Ag-1 Cu-0.1 Ni	Partial	800	33.8	21.4	40.0	97.7
		Full	1200	30.5	11.4	40.0	97.1
27	Ag-1 Cu-0.2 Ni	Partial	800	34.2	21.4	37.5	97.2
		Full	1200	30.4	12.1	39.3	97.1
28	Ag-1.5 Cu-0.1 Ni	Partial	800	35.6	24.4	32.5	95.8
		Full	1200	31.8	11.7	38.6	93.5
29	Ag-1.5 Cu-0.2 Ni	Partial	800	31.0	25.5	31.0	96.1
		Full	1400	30.8	9.5	37.2	89.8

(a) Alloy wires annealed for 1 hour and air cooled.

(b) This elongation value is not considered representative of the fully annealed condition in this alloy. Rather the value is lower than expected, probably as a result of the very large grain size developed in this alloy during the 1400 F treatment.

tensile elongations only slightly below those for the fully annealed condition. Partially annealed Alloys 28 and 29 had electrical conductivities above the fully annealed values, while Alloys 23, 26, and 27 had the fully annealed conductivities. The conductivity of Alloy 2 was reduced only 2.3 percent IACS by partial annealing.

Additional Studies of Promising Alloys

Based primarily on the tensile and electrical conductivity properties of the 30 experimental alloys in the various processed conditions, the alloys listed in Table 11 were selected as the best candidates for further investigation. Pure silver and the Ag-0.5 Pd, Ag-0.1 Cr, and Ag-0.1 Be alloys, with strengths below 30,000 psi, were included on the basis that their corrosion resistance or fabricability may be superior to those properties of the alloys with copper.

TABLE 11. SILVER-BASE ALLOYS SHOWING PROMISE FOR LEAD-WIRE USE

Alloy	Intended Composition, weight percent	Actual Composition, weight percent
1	Ag	99.98+ Ag
2	Ag-1.5 Cu	Ag-1.5 Cu
5	Ag-0.5 Pd	Ag-0.5 Pd
12	Ag-0.2 Ni	Ag-0.21 Ni
14	Ag-0.1 Cr	Ag-0.06 Cr
22	Ag-0.1 Be	Ag-0.078 Be
23	Ag-0.2 Be	Ag-1 Cu-0.2 Be
26	Ag-1 Cu-0.1 Ni	Ag-1.05 Cu-0.12 Ni
27	Ag-1 Cu-0.2 Ni	Ag-1.0 Cu-0.15 Ni
28	Ag-1.5 Cu-0.1 Ni	Ag-1.45 Cu-0.10 Ni
29	Ag-1.5 Cu-0.2 Ni	Ag-1.5 Cu-0.22 Ni

As shown in Table 11, the actual compositions of the selected alloys were very near to the compositions intended; however, Alloy 23 contained about 1 percent copper in addition to the 0.2 percent beryllium intended. This copper was inadvertently added to Alloy 23 during melting when a copper rod was used to remove slag from the melt surface.

Flexure-Breakage Properties

Results of flexure-breakage tests on alloys showing promise of meeting lead-wire requirements were evaluated on fully annealed, partially annealed, and cold-worked wires. All conditions were exposed at 700 F before flexure tests were conducted. The results are summarized in Table 12. Individual test results used to compute the average values given in Table 12 are given in Appendix C, Table C-6. These flexure breakage results were obtained by cyclically bending 0.050-inch-diameter wire

TABLE 12. FLEXURE-BREAKAGE PROPERTIES OF PURE SILVER AND THE SELECTED ALLOYS[a]

Alloy	Composition, weight percent	Condition Before 700 F Exposure	Average Number of Bend Cycles to Failure After Exposure at 700 F for 2 Minutes[b]
0	Ag	Fully annealed, 1 hour 800 F	60
		Worked 30 percent RA	48
2	Ag-1.5 Cu	Fully annealed, 1 hour 1000 F	68
		Partially annealed, 1 hour 800 F	43
		Worked 30 percent RA	42
5	Ag-0.5 Pd	Fully annealed, 1 hour 1200 F	53
		Worked 30 percent RA	47
12	Ag-0.2 Ni	Fully annealed, 1 hour 1400 F	64
		Worked 30 percent RA	41
14	Ag-0.1 Cr	Fully annealed, 1 hour 1400 F	56
		Partially annealed, 1 hour 1000 F	52
		Worked 63 percent RA	59
22	Ag-0.1 Be	Fully annealed, 1 hour 1200 F	44
		Worked 15 percent RA	60
23	Ag-1 Cu-0.2 Be	Fully annealed, 1 hour 1400 F	41
		Partially annealed, 1 hour 800 F	38
		Worked 15 percent RA	42
26	Ag-1 Cu-0.1 Ni	Fully annealed, 1 hour 1200 F	53
		Partially annealed, 1 hour 800 F	51
		Worked 8 percent RA	50
27	Ag-1 Cu-0.2 Ni	Fully annealed, 1 hour 1200 F	54
		Partially annealed, 1 hour 800 F	45
		Worked 30 percent RA	35
28	Ag-1.5 Cu-0.1 Ni	Fully annealed, 1 hour 1200 F	61
		Partially annealed, 1 hour 800 F	50
		Worked 8 percent RA	40
29	Ag-1.5 Cu-0.2 Ni	Fully annealed, 1 hour 1400 F	79
		Partially annealed, 1 hour 800 F	45
		Worked 8 percent RA	43

(a) Average values of four tests on each alloy condition are given.

(b) 0.050-inch-diameter wire specimens were bent over a 0.10-inch radius through an angle of 95 degrees. A tensile load of 330 grams (3.7 ksi) was applied to the specimens during the tests. Four tests usually form basis of average.

specimens through an angle of 95 degrees over a 0.1-inch radius. A load of 330 grams (3,700 psi) was applied to the wires during the flexure-breakage tests.

As shown in Table 12, the Ag-1.5 Cu, Ag-0.2 Ni, Ag-1.5 Cu-0.1 Ni, and Ag-1.5 Cu-0.2 Ni alloys in the fully annealed condition endured a greater average number of bend cycles before failure than pure silver or the other alloys. Also shown in Table 12 is that the flexure-breakage lives of the partially annealed, and usually the cold worked, alloys containing copper were less than for the fully annealed conditions.

Corrosion and Oxidation Behavior

No corrosion was detected on pure silver or on seven representative silver alloys after 1,512 hours of alternate immersion, in a solution of water:2 percent hydrofluoric acid:5 percent sodium fluoride. This excellent corrosion resistance was exhibited by the silver materials regardless of composition or of processing condition (fully annealed, partially annealed, or cold worked). The data in Table 13 show that changes in the weight of corrosion specimens, due to loss of material as corrosion products, was less than the accuracy (±0.0005 g) of the balance used to make the weight measurements.

Selected alloys were heated in air for 2 minutes at 700 F to determine if oxide films would form on their surfaces during the Teflon-curing cycle. The oxidized specimens were visually examined for surface discoloration indicative of oxide films. Results of these observations are given in Table 14.

Only the alloys containing copper in the worked condition or as partially annealed at 800 F were discolored by the 700 F exposure in air. This discoloration, which was uniform over the wire surfaces, was caused by the oxidation of microscopic copper-rich areas at the specimen surfaces. Significantly, the binary alloys containing copper did not discolor during heating in air after being annealed at temperatures above 1000 F. This result is explainable by the fact that 1.5 percent of copper is completely soluble in silver at temperatures above 800 F. As a result, when a two-phase silver alloy containing 1.5 percent or less copper is heated to temperatures above 800 F, the alloy becomes a single-phase solid solution of copper in silver. This single-phase structure is retained at room temperature by air cooling the wire from the annealing treatment. The single-phase alloy does not discolor during the 700 F exposure because there are no copper-rich areas present in the structure.

Also noteworthy is that Alloys 26 and 27 containing 1 percent copper with 0.1 and 0.2 percent nickel, respectively, did not discolor significantly during the 700 F exposure after being annealed at 800 F.

Solderability of Alloys Containing Copper

The possibility that the oxide film which formed on some of the alloys containing copper might impair solderability was investigated by making solder joints between two 0.050-inch-diameter wires of those alloys with the thickest oxide films. These joints were made with a hand soldering gun and 50 tin-50 lead, resin-core solder. The solder was flowed into the cavity formed by positioning two wires in contact side by side with an overlap of 1/2 inch. No difficulties were encountered in wetting the oxides with solder. Excellent adhesion of solder to the oxidized wires was observed on the basis

TABLE 13. CORROSION BEHAVIOR OF SILVER-ALLOY WIRE IN ALTERNATE IMMERSION TEST IN WATER: 2 PERCENT HYDROFLUORIC ACID: 5 PERCENT SODIUM FLUORIDE

Alloy	Composition, weight percent	Alloy Condition: 1 Hour Annealing Temperature, F	Alloy Condition: Degree of Cold Work, percent RA	Change in Weight of Specimen After 1,512 Hours, grams
0	Ag	800	--	+ 0.0002
0	Ag	--	30	0.0000
2	Ag-1.5 Cu	1000	--	0.0000
2	Ag-1.5 Cu	800	--	- 0.0002
2	Ag-1.5 Cu	--	30	- 0.0001
5	Ag-0.5 Pd	1200	--	0.0000
7	Ag-1 Au	800	--	0.0000
12	Ag-0.2 Ni	1400	--	0.0000
12	Ag-0.2 Ni	--	30	+ 0.0001
14	Ag-0.1 Cr	1000	--	+ 0.0002
14	Ag-0.1 Cr	1400	--	+ 0.0002
14	Ag-0.1 Cr	--	63	+ 0.0002
27	Ag-1 Cu-0.2 Ni	800	--	+ 0.0003
27	Ag-1 Cu-0.2 Ni	1200	--	+ 0.0001
27	Ag-1 Cu-0.2 Ni	--	30	0.0000
29	Ag-1.5 Cu-0.2 Ni	800	--	0.0000
29	Ag-1.5 Cu-0.2 Ni	1400	--	0.0000
29	Ag-1.5 Cu-0.2 Ni	--	8	0.0000

TABLE 14. OBSERVATIONS OF THE DISCOLORATION PRODUCED BY EXPOSING PURE SILVER AND THE SELECTED ALLOYS TO THE SIMULATED TEFLON-CURING CYCLE (2 MINUTES AT 700 F IN AIR)

Alloy	Composition, weight percent	Condition Before Exposure in Air for 2 Minutes at 700 F	Color of Wire After 700 F Exposure
0	Ag	Worked 30 percent RA	Silver
		Annealed at 800 F	Silver
2	Ag-1.5 Cu	Worked 30 percent RA	Bronze
		Annealed at 800 F	Bronze
		Annealed at 1000 F	Dull silver
5	Ag-0.5 Pd	Worked 30 percent RA	Silver
		Annealed at 1200 F	Dull silver
12	Ag-0.2 Ni	Worked 30 percent RA	Dull silver
		Annealed at 1400 F	Dull silver
14	Ag-0.1 Cr	Worked 63 percent RA	Dull silver
		Annealed at 1000 F	Dull silver
		Annealed at 1400 F	Dull silver
22	Ag-0.1 Be	Worked 15 percent RA	Dull silver
		Annealed at 1200 F	Gray silver
23	Ag-1 Cu-0.2 Be	Worked 15 percent RA	Dull silver
		Annealed at 800 F	Dull silver
		Annealed at 1400 F	Gray
26	Ag-1 Cu-0.1 Ni	Worked 8 percent RA	Brass
		Annealed at 800 F	Red silver
		Annealed at 1200 F	Yellow silver
27	Ag-1 Cu-0.2 Ni	Worked 30 percent RA	Brass
		Annealed at 800 F	Yellow silver
		Annealed at 1200 F	Dull silver
28	Ag-1.5 Cu-0.1 Ni	Worked 8 percent RA	Dark brass
		Annealed at 800 F	Dark brass
		Annealed at 1200 F	Dull silver
29	Ag-1.5 Cu-0.2 Ni	Worked 8 percent RA	Dark brass
		Annealed at 800 F	Dark brass
		Annealed at 1400 F	Dull silver

that soldered joints failed in tension by shear through the solder. No failures occurred at the solder-oxide interface. Excellent wetting and adhesion of solder to the silver alloys not containing copper was also observed.

Although no degradation of solderability resulted on the alloys with surface oxides, discoloration of the wires may be undesirable to NASA. Inspectors have been trained to reject slip-ring lead wires which have copper oxide, "red plague", spots on them. Such practice might cause rejection of good lead wires of the silver alloys if the copper oxide color was spotty.

Selection of Alloys for Scale-Up

Studies of experimental-alloy wires at 0.050-inch suggested that three alloys looked especially promising for lead-wire use. These were Ag-1.5 Cu (Alloy 2), Ag-0.2 Ni (Alloy 12), and Ag-1.0 Cu-0.2 Ni (Alloy 27).

The Ag-1.5 Cu alloy was selected on the basis of adequate strength in the annealed condition and good conductivity. This alloy has the added advantage of being available commercially. Although superior strength was available in alloys with higher copper, it was thought desirable to avoid larger amounts of copper so as to minimize the opportunity for corrosion and oxidation.

It was considered advisable to include at least one copper-free alloy in the final evaluation program in case oxidation or corrosion of the alloys with copper proved more troublesome than anticipated. The Ag-0.2 Ni composition was selected for this reason. Although the properties of this alloy are not significantly better than the properties of the other dispersion alloys, it was selected principally because it was easier to manufacture than the other alloys.

The Ag-1.0 Cu-0.2 Ni alloy was one of the best alloys prepared in this program. Although the ternary Ag-Cu-Ni alloys containing 1.5 Cu had appreciably longer flex lives than the Ag-1 Cu-0.2 Ni composition, their strengths were not significantly higher and it was decided to scale-up an alloy with a lower copper content to minimize the chances of corrosion and a higher nickel content to maximize the softening temperature.

Since most of the alloy studies were conducted on a fairly heavy wire gage, additional work on finer wire was desirable before final selection of alloys for scale-up. Accordingly, tensile properties, electrical conductivity, and flexure-breakage life were determined on 0.010-inch-diameter wire of Alloy 27 (Ag-1 Cu-0.2 Ni) after several different annealing treatments plus the 700 F exposure. This evaluation was conducted to determine:

(1) If the properties of fine wire, from an alloy containing copper, are altered by exposure in air at 700 F

(2) If fine wire can be annealed in air rather than in an inert atmosphere, without degradation of properties

(3) If better properties could be obtained in fine wire of Alloy 27 by annealing it at temperatures of 600 or 1000 F, rather than the 800 F or 1200 F temperatures investigated with 0.050-inch-diameter wire.

Average results of these studies on Alloy 27 (Ag-1 Cu-0.2 Ni) are given in Table 15. All the results are given in Appendix C, Table C-7.

Comparison of the properties in Table 15 of argon-annealed Alloy 27 of the small-diameter wire, before and after exposure at 700 F, show that the tensile strengths were only slightly affected by the exposure. The elongation values were slightly improved but the flexure-breakage life was apparently reduced. This reduction of flexure-breakage life is questionable since only a limited number of bend tests were run. Most likely, the properties of fine wire in the annealed condition are little affected by the 700 F exposure.

Comparison of the tensile properties in Table 15 of exposed specimens, annealed in argon, with the properties of the specimens annealed in air show that the properties of specimens annealed at 600 F were similar. However, the strengths of specimens annealed at 800 and 1000 F in air were 30 to 40 percent higher than the strengths of the specimens annealed at 800 and 1000 F in argon. These increased strengths of the air-annealed specimens are thought to be the result of internal oxidation. Small particles of oxide formed by reaction of alloy elements with oxygen diffusing into the alloy produce a dispersion-hardening effect. (Several commercial silver alloys containing magnesium or cadmium are internally oxidized to achieve strengths as high as 70 ksi.)

The dispersed particles tend to lock in or preserve the strengthening effects of cold work as well as to exert their own strengthening effects by straining the crystal lattice. As the annealing temperature is increased, annealing effects which eliminate the wrought structure gradually overcome the locking effects of the dispersed phase. The strength is reduced although some strengthening due to the presence of the dispersed phase will persist until the dispersed particles exceed a critical size. Predominance of annealing effects is demonstrated by the tensile strengths of the specimens annealed at 1200 F. As shown in Table 15, the specimens annealed in air at 1200 F have a tensile strength about 20 percent greater than the strength of the specimen annealed in argon, indicating some dispersion strengthening. But, the strength of the specimen annealed in air at 1200 F is about 17 percent below the strengths of the specimens annealed in air at 800 and 1000 F, indicating that annealing effects have reduced the strength imparted by the wrought structure.

The properties of the argon-annealed specimens, given in Table 15, show that the flexure-breakage life is longest (72 cycles) for specimens annealed at 1000 F. However, specimens annealed in argon at 800 F had only slightly shorter flexure-breakage lives (65 cycles) and had a yield strength 7 ksi higher than for the specimens annealed at 1000 F.

The flexure-breakage life of the specimens annealed in air appeared to be higher than for specimens annealed in argon after exposure to the 700 F treatment.

In agreement with the discoloration behavior reported in Table 14, specimens annealed at 800 F were slightly discolored after the air exposure, while specimens annealed at 1000 F were not affected.

The data indicate that an annealing temperature of 900 F would give an optimum combination of tensile strength, flexure-breakage life, and resistance to discoloration.

In preparing 42-gage wire (0.0025 inch), using commercial processing, strand annealing may be required. Strand annealing is a continuous method of annealing wires

TABLE 15. AVERAGE PROPERTIES OF 0.010-INCH-DIAMETER WIRE OF ALLOY 27 (Ag-1 Cu-0.2 Ni) IN SEVERAL CONDITIONS

Condition: Annealed for 1 Hour: Annealing Temperature, F	Condition: Annealed for 1 Hour: Annealing Atmosphere	Condition: Worked, percent reduction the area	Tensile Properties at 75 F: Ultimate Strength, ksi	Tensile Properties at 75 F: 0.2 Percent Offset Yield Strength, ksi	Tensile Properties at 75 F: Elongation, percent in 10 inches	Bend Cycles to Failure[a]	Electrical Conductivity, percent IACS
			Worked Condition				
--	--	17	39.8	38.2	1.5	57	--
			Annealed Condition Before 700 F Exposure				
600	Argon	--	35.7	29.4	15.4	60	--
800	Argon	--	31.9	21.4	26.9	64	97.2
1000	Argon	--	31.1	14.2	33.4	72	--
1200	Argon	--	30.5	10.2	28.9	52	97.1
			After Exposure at 700 F in Air for 2 Minutes				
--	--	17	37.4	33.2	11.9	51	--
600	Argon	--	34.2	27.9	18.8	34	--
800	Argon	--	31.9	21.3	30.2	54	--
1000	Argon	--	30.7	14.1	34.3	53	--
1200	Argon	--	30.5	11.3	29.4	40	--
600	Air	--	34.5	27.7	19.7	68	--
800	Air	--	42.1	31.8	15.7	58	100.1
1000	Air	--	43.0	29.9	16.5	72	96.7
1200	Air	--	36.2	20.0	21.9	69	--

(a) Specimens were bent over a 0.05-inch radius. A tensile load of 100 grams (2.8-ksi stress) was applied to the wires during the bend tests.

and is accomplished by pulling wires through a hot furnace at speeds of about 100 feet per minute. To determine the strand-annealing temperatures for producing optimum properties in the silver slip-ring lead wires and to obtain additional data on the properties of fine wire, strand-annealing studies were conducted on 0.0027-inch-diameter wires of the three most promising alloys and pure silver. Wires 0.0027-inch in diameter of alternate dispersion compositions, Alloy 14 (Ag-0.1 Cr) and Alloy 22 (Ag-0.1 Be), were also included in the strand-annealing studies to determine if the properties of these alloys in the form of fine wire were still inferior compared with the properties of the alloys selected for scale-up.

To duplicate the time at temperature, about 5 seconds, that wires will experience when pulled at a rate of 100 feet per minute through an 8-foot-long furnace, a treatment typically used for commercial strand annealing, the wires annealed at Battelle were pulled at a speed of 47 inches per minute through a 3-inch-long hot zone. The wires were protected from oxidation during the strand annealing by using a reducing gas in the furnace. In addition to the specimens of Alloys 14 and 22, which were strand annealed in reducing gas to prevent oxidation, other specimens of Alloys 14 and 22 were strand annealed in air to determine if internal oxidation of chromium or beryllium might produce increased strengths.

Properties of the strand-annealed wires are given in Table 16. The data in Table 16 show that the yield strength of the silver alloys decreases more rapidly with increasing annealing temperatures than does the ultimate strength. Elongation concurrently increases with higher annealing temperatures, until the alloy is fully annealed. Electrical conductivity also is increased by annealing. In general, the flexure-breakage life of the alloys selected for scale-up decreases with higher annealing temperatures. This is counter to the indication from the tests conducted on heavier wires. Some of the bend data in Table 16 do not follow this trend; this is attributed to premature failure of specimens due to imperfections in the wire surfaces.

Comparison of the properties of the alloys evaluated in the strand-annealed condition shows that Alloys 2 (Ag-1.5 Cu), 12 (Ag-0.2 Ni), and 27 (Ag-1 Cu-0.2 Ni) have higher strength than the other two alloys, while the elongations, flexure-breakage lives, and electrical conductivities are similar. All of these alloys have significantly higher strengths and longer flexure-breakage lives than pure silver.

Comparison of the data in Table 16 for specimens of Alloys 14 and 22, which were annealed in reducing gas and air, shows that the strengths were not much affected by the annealing atmosphere, although both yield strengths and elongation of specimens annealed at 1200 F suggested initiation of internal oxidation. The diffusion of oxygen into silver is time and temperature dependent. Markedly increased strength in air-annealed specimens of Alloys 14 and 22 probably did not occur because the wires were not heated to a sufficiently high temperature for a sufficiently long time. Oxygen was not absorbed to the extent required to effect gross internal oxidation of the alloy elements.

Strand-annealing temperatures that produced optimum properties for slip-ring lead wires of the most promising alloys are given below. Two annealing temperatures are of interest for finishing Alloy 27. Both temperatures produce nearly equivalent ultimate strengths, elongations, and electrical conductivities, but the yield strength and flexure-breakage life produced by the 1000 F annealing temperature are appreciably higher than for the 1200 F annealed condition. The 1000 F annealing temperature

TABLE 16. EFFECT OF STRAND-ANNEALING TEMPERATURES ON THE PROPERTIES OF 42-GAGE WIRES OF THE SCALE-UP ALLOYS AND PURE SILVER

Average values are reported

Strand Annealing Temperature, F[a]	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation, percent in 10 inches	Bend Cycles to Failure Over a 0.025-Inch Radius[b]	Electrical Conductivity, percent IACS
		Pure Silver			
500	25.0	13.4	16.1	--	--
750	26.7	12.6	24.0	36	105
800	26.5	12.6	24.5	42	--
850	20.6	15.4	21.6	34	--
900	25.3	10.9	23.3	36	--
		Alloy 2 (Ag-1.5 Cu)			
500	88.7	84.9	1.6	--	89.8
750	43.2	36.9	3.3	174	--
850	38.3	32.1	8.3	57	98.5
950	33.0	21.7	29.3	67	100.3
1000	32.0	21.5	20.9	46	105.0
1100	32.1	14.1	29.9	51	--
1200	30.6	11.2	26.0	50	100.3
1400	22.5	12.7	9.4	36	--
		Alloy 12 (Ag-0.2 Ni)			
500	35.4	29.7	1.5	53	108.0
750	30.8	17.3	16.4	40	110.3
900	30.3	16.5	19.1	56	109.6
1000	29.8	15.1	19.9	53	--
1100	30.0	15.0	20.1	47	109.8
1400	28.4	13.3	20.4	47	--
		Alloy 27 (Ag-1 Cu-0.2 Ni)			
500	76.3	69.3	2.4	413	--
700	44.8	38.1	1.8	446	99.5
750	42.3	35.7	1.9	--	--
850	36.9	31.0	6.8	133	101.5
900	34.5	26.8	12.7	57	--
950	33.8	25.1	15.4	46	101.2
1000	32.0	18.9	23.0	67	102.7
1100	31.9	15.3	24.2	48	--
1200	31.7	14.1	24.9	50	102.7
1400	30.3	11.9	25.0	43	--

TABLE 16. (Continued)

Strand Annealing Temperature, F[a]	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation, percent in 10 inches	Bend Cycles to Failure Over a 0.025-Inch Radius[b]	Electrical Conductivity, percent IACS
		Alloy 14 (Ag-0.1 Cr) Annealed in reducing gas			
750	27.9	16.0	23.2	35	106.4
850	27.6	12.4	24.9	37	106.4
1000	27.2	12.6	24.3	35	--
1200	26.6	10.4	24.5	43	105.3
		Alloy 14 (Ag-0.1 Cr) Annealed in air			
500	28.7	16.9	18.4	39	--
700	27.9	13.8	23.2	37	--
900	27.8	13.4	24.7	37	105.6
1200	26.6	14.1	18.4	41	105.1
		Alloy 22 (Ag-0.1 Be) Annealed in reducing gas			
750	30.3	17.7	22.3	50	105.6
850	30.5	16.7	29.1	51	106.4
1000	30.1	13.5	31.5	52	--
1200	29.3	11.8	28.9	60	105.3
		Alloy 22 (Ag-0.1 Be) Annealed in air			
500	35.5	30.8	3.2	--	--
700	30.9	18.5	27.7	51	--
900	30.8	16.4	29.5	55	105.1
1200	30.8	14.4	24.5	42	103.9

(a) Specimens were at temperature about 4 seconds when pulled through a 3-inch-long hot zone at 47 inches-per-minute.
(b) A tensile load of 14 grams (6000 psi) was applied to the wire specimens during the bend test.

produces a partially annealed structure where some of the strength improvement from cold work is retained. At 1200 F, the structure is fully annealed.

			Properties Produced by Strand Annealing 41-Gage Wire at the Indicated Temperature				
Alloy	Alloy Composition	Strand Annealing Temperature, F	Ultimate Tensile Strength, ksi	Yield Strength, ksi	Elongation, percent	Flexure-Breakage Life Over 0.025-Inch Radius, cycles	Electrical Conductivity, percent IACS
0	Ag	750	26.7	12.6	24	36	105
2	Ag-1.5 Cu	1200	30.6	11.2	26	50	100
12	Ag-0.2 Ni	1100	30.0	15.0	20	47	110
27	Ag-1 Cu-0.2 Ni	1000	32.0	18.9	23	67	103
27	Ag-1 Cu-0.2 Ni	1200	31.7	14.1	25	50	103

On the basis of these studies, it was concluded in the scale-up program that Alloys 2 (Ag-1.5 Cu) and 12 (Ag-0.2 Ni) should be finished as 19-strand, 42-gage lead wire in the fully annealed temper. Alloy 27 (Ag-1.0 Cu-0.2 Ni), however, should be finished in two tempers, partially annealed and fully annealed, to permit a further comparison of these two conditions.

RESULTS OF ALLOY SCALE-UP PROGRAM

The three alloys A (Ag-1.5 Cu), B (Ag-0.2 Ni), and C (Ag-1 Cu-0.2 Ni) selected to be scaled-up to commercially produced lead wire, were cast and fabricated to rod at Battelle. Pure silver to be scaled-up was purchased by Battelle as 0.062-inch-diameter wire with a purity of 99.99 percent silver. The alloy rods and pure silver were drawn to 42-gage wire and stranded to 19-strand lead wire at the Hudson Wire Company. They were insulated with Teflon at the Philadelphia Insulated Wire Company. Alloys A and B and pure silver were prepared in the fully annealed condition. Alloy C was prepared in two tempers, partially annealed and fully annealed. Portions of the finished lead wires were evaluated at Battelle. The balance of the wires was supplied to NASA for more detailed study.

Casting of Scale-Up Alloys

Three ingots, weighing 16.6 pounds, were cast from melts of the scale-up alloys prepared in a graphite crucible using induction heating. Pure silver sheet of 99.99 fine was used for melting stock to avoid introduction of oxygen as occurred when silver shot was used for melting stock during the laboratory studies. The sheet stock had not been deoxidized with phosphorus or lithium. The alloys were melted under a hydrogen cover and were deoxidized with bubbling hydrogen. Following homogenization of the alloys in the molten condition, a hole in the bottom of the melting crucible was opened allowing the molten alloys to flow through a graphite tube into a copper mold positioned below the furnace. This method of pouring prevented the pickup of oxygen that would have occurred if the molten silver had been poured from the top of the furnace through air. The time-temperature sequences used to prepare the scale-up ingots are given in Appendix D, Table D-1.

The 16.6-pound ingots were cast in the shape of a conical frustum with a height of 6-1/2 inches and end diameters of 3 and 2 inches. Cylindrical hot tops were cast on the ingot tops to provide a reservoir of molten metal for filling shrinkage voids in the ingots as solidification occurred.

The results of spectrographic analyses given below show that the chemical compositions of the ingots were within 0.1 percent of the intended compositions and were homogeneous over the ingots' length.

Alloy	Intended Composition, weight percent	Chemical Composition at the Following Ingot Locations, weight percent: Top	Bottom
A	Ag-1.5 Cu	Ag-1.4 Cu	Ag-1.4 Cu
B	Ag-0.2 Ni	Ag-0.19 Ni	Ag-0.20 Ni
C	Ag-1 Cu-0.2 Ni	Ag-0.9 Cu-0.17 Ni	Ag-0.9 Cu-0.18 Ni

Radiographs of the ingots revealed that Alloy B (Ag-0.2 Ni) was free of porosity throughout the ingot. Alloys A (Ag-1.5 Cu) and C (Ag-1.0 Cu-0.2 Ni) contained some small centerline voids near the ingot tops. However, ~~these slightly~~ porous regions were discarded during preliminary fabrication so that only dense material was drawn to 42-gage wire.

Fabrication to Rod at Battelle

Commercial methods, known to produce the highest quality wire, were used to fabricate the ingots to 0.121-inch diameter at Battelle. Before fabrication of the ingots, the hot tops and bottoms were cut off, leaving about 12 pounds of each alloy. These 12-pound portions were heated to 1100 F and were forged to cylinders with a diameter of 3-3/16 inches and a height of about 4-1/2 inches. Oxidized material was removed from the forgings by machining them to a diameter of 3.125 inches. The machined forgings were heated to 1500 F and were extruded to 0.188-inch-diameter rod in a single extrusion operation. The reduction of area 305:1 (ratio of cross-section areas before and after extrusion) produced by this extrusion operation is not unusual for highly ductile silver alloys. About 10-1/2 pounds of extruded rod was obtained from the 12-pound billets. From this amount, about 15 feet or 2 pounds of rod was discarded from the tail end of each extrusion to eliminate defects in the rod core. The remaining 8-1/2 pounds of each extrusion was drawn at room temperature to 0.121-inch diameter using reductions of one B & S number per pass.

The 0.188-inch-diameter rod produced by extrusion had a very good surface finish and was free of internal defects over the front 70 feet of each extrusion. The defects observed in the core of extruded rod, at the tail end, occurred because the extrusion butt was only 1/4 inch in thickness in an attempt to obtain the maximum yield of extruded rod. During the final stages of the extrusion operation, the surface of the billets flowed into the rod core and created voids.

Pressures required to initiate and sustain extrusion of the alloys are given in Table 17. As shown in this table, higher pressures were required to extrude the alloys containing copper than were required to extrude the Ag-0.2 Ni alloy. These higher pressures required for the copper-containing alloys reflects their higher softening resistances and elevated-temperature strengths.

TABLE 17. EXTRUSION BEHAVIOR OF SILVER ALLOYS

Alloy	Composition, weight percent	Billet Temperature, F	Extrusion Rate, feet of 0.188-inch-diameter wire per minute: Start	Runout	Extrusion Pressure, ksi: Breakthrough	Runout
A	Ag-1.4 Cu	1500	75	44	143	131
B	Ag-0.2 Ni	1500	75	44	128	107
C	Ag-0.9 Cu-0.18 Ni	1500	75	44	143	130

The extruded rod was drawn from 0.188-inch diameter to 0.121-inch diameter at Battelle. All the extruded rod exhibited good fabricability and was readily drawn to 56 percent reduction in area at room temperature.

Fabrication of Lead Wires at the Hudson Wire Company

With approval of Mr. Estel G. Lowe at NASA, Project Monitor, and Mr. James W. Fletcher, Contracting Officer, the 8-1/2-pound portions of 0.121-inch-diameter rod of each of the scaled-up alloys A, B, and C and the 20 pounds of pure silver 0.062-inch-diameter wire were shipped to the Hudson Wire Company for processing to 19-strand, 42-gage lead wires. This work at Hudson was accomplished under a subcontract from Battelle. Hudson was supplied with detailed fabrication and annealing data on the alloys and pure silver and was instructed to achieve the properties listed in Table 18.

TABLE 18. TENSILE PROPERTIES DESIRED OF 42-GAGE WIRES OF THE EXPERIMENTAL ALLOYS IN ANNEALED CONDITIONS[a]

Alloy	Condition	Minimum Ultimate Tensile Strength, ksi	Range of 0.2 Percent Offset Yield Strength, ksi	Minimum Elongation, percent in 10 inches
Ag	Fully annealed	25	7-12	24
A (Ag-1.5 Cu)	Fully annealed	30	8-13	24
B (Ag-0.2 Ni)	Fully annealed	29	9-14	20
C (Ag-1.0 Cu-0.2 Ni)	Partially annealed	32	20-25	15
	Fully annealed	31	11-16	24

(a) Specimens are to be tested at a strain rate of 0.1 in./in./minute.

Drawing of Silver Materials to 42 Gage

Preliminary tensile tests by Hudson on the materials received from Battelle showed that all the rods and wire had high ductility and high strength. On these bases, the materials were judged fabricable in the as-received conditions. Results of the tensile tests on the starting materials are given in Appendix D, Table D-2.

The alloy rods were subsequently drawn from 0.121-inch diameter to 0.064-inch diameter, at room temperature, using a Syncro wire drawing machine employing multiple dies. Drawing speed was 1000 feet per minute with reductions of one B & S number per die. A soap solution containing 3 to 5 percent fat was used to lubricate the wires and dies during these initial drawing operations. After being drawn to 0.064-inch diameter, the ductilities of the alloys, as measured by reduction in area, were adequate for further drawing without an intermediate anneal.

The alloys, along with pure silver, were then drawn from 0.064-inch diameter to 0.0102-inch diameter at a rate of 2500 feet per minute on the Syncro machine. During this operation, a commercial lubricant, Lusol, was used with reductions of one B & S number per die.

No unusual breakage of wires, wire scratching, or die wear occurred during these drawing operations to produce 0.0102-inch wire.

At 0.0102-inch diameter, the wires were strand annealed in a reducing atmosphere of dissociated ammonia (75 percent hydrogen-25 percent nitrogen). The annealing temperatures used and the properties produced in the annealed, 0.010-inch wires are given in Table 19. As shown in Table 19, these annealing treatments produced high ductilities so that the wires could be drawn to the finished size, 42 gage (0.0025-inch diameter).

TABLE 19. PROPERTIES OF 0.0102-INCH-DIAMETER WIRES AFTER INTERMEDIATE ANNEALING TREATMENT[a]

Wire	Strand Annealing Temperature, F	Ultimate Tensile Strength, ksi	Elongation in 10 Inches, percent	Electrical Conductivity at 74 F, percent IACS
Pure silver	700	28.1	26	103
Alloy A	1050	33.1	34	93.5
Alloy B	900	29.7	27	96.2
Alloy C	1000	32.7	21	96.6

(a) Wires were strand annealed by pulling them through a 4-foot-long oven at a rate of 100 feet per minute.

The final drawing operation from 0.0102-inch diameter to 0.0025-inch diameter was performed on a multiple die, tub-type, upright machine. The drawing speed was about 800 feet per minute using one B & S reduction per die. A soap solution containing about 0.3 percent fat was used as the drawing lubricant.

Pure silver and Alloys B and C were readily drawn from 0.0102-inch to 42-gage without an unusual number of breaks in the wires during drawing. Alloy A, on the other hand, was difficult to draw to final size because of frequent wire failures. The cause of the breakage of Alloy A was not determined.

Diamond-faced dies were used for all the drawing operations. Special dies, having a short bearing length (20-40 percent of the die diameter) were used from 0.057-inch through 42-gage. Standard dies, used for drawing copper, were employed at diameters above 0.057 inch.

Stranding of 42-Gage Wire to 19/42 Cable

The 42-gage wires, in the wrought condition, were stranded into 19-strand cable using a tubular-type stranding machine. Difficulty of stranding the various silver materials was evaluated by the number of breaks which occurred in the wires per pound of wire stranded. As shown below, pure silver and Alloys A and C stranded much better than Alloy B.

Wire	Breaks per Pound During Stranding
Pure Silver	0.59
Alloy A	0.68
Alloy C	0.73
Alloy B	1.78

No reason was given for the poor stranding behavior of Alloy B.

Heat Treatment of 19/42 Cables

Based on the strand-annealing data provided by Battelle, the Hudson Wire Company conducted brief annealing studies on Alloys A and B and pure silver to determine the temperature that would fully anneal the wrought materials when they were pulled through a 4-foot-long oven at 100 feet per minute. The temperatures for full annealing were found to be 950 F, 800 F, and 700 F for Alloys A and B, and pure silver, respectively. Based on the annealing data generated on Alloy C, Hudson selected temperatures of 850 and 1050 F to achieve the partially annealed and fully annealed properties.

The final annealing treatments were done in an atmosphere of dissociated ammonia (75 percent hydrogen-25 percent nitrogen) in a 4-foot-long oven, pulling the wires through the oven at a rate of 100 feet per minute.

All the silver materials were bright after the annealing treatments and no sticking together of single strands within the cables could be detected.

Inventory of Cable Produced by the Hudson Wire Company From the Scaled-Up Alloys

As shown by the data in Table 20, the yield of finished 19/42 cable from the scaled-up silver materials ranged from 42 percent for pure silver to 52 percent for

TABLE 20. INVENTORY OF 19/42 CABLE PRODUCED FROM THE CANDIDATE LEAD-WIRE ALLOYS

Wire	Number of Pieces	Weight of Pieces, pound	Calculated Length of 19/42 Cable, feet	Yield from Material Supplied, percent
Pure Silver	5	2.94	6,202	
		2.69	5,675	
		1.06	2,236	
		0.93	1,962	
		0.81	1,708	
	Total	8.43	17,783	42
Alloy A	3	2.01	4,240	
		1.36	2,869	
		1.08	2,278	
	Total	4.45	9,387	52
Alloy B	7	0.90	1,898	
		0.60	1,265	
		0.52	1,097	
		0.50	1,054	
		0.47	991	
		0.45	949	
	Total	3.94	8,308	46
Alloy C, fully annealed	1	2.54	5,358	
Alloy C, partially annealed	2	1.10	2,320	
		0.64	1,350	
	Total	1.74	3,670	50

Alloy A. According to personnel at the Hudson Wire Company, these apparently low yields are considered satisfactory on the basis that these were experimental materials and the yield from silver-plated copper is only slightly better.

Teflon Coating of Stranded Wire at the Philadelphia Insulated Wire Company

With the approval of Mr. Estel G. Lowe at NASA, Project Monitor, and Mr. James W. Fletcher, Contracting Officer, sufficient lengths of 19/42 cable of Alloys A, B, and C (fully annealed) and pure silver were shipped to the Philadelphia Insulated Wire Company to obtain about 5,000 feet of Teflon-insulated lead wires. Sufficient length of 19/42 cable was not available from Alloy C, in the partially annealed temper, to obtain 5,000 feet. Thus, best effort yield of insulated wire was requested from the 3,600 feet supplied.

The Philadelphia Insulated Wire Company was instructed to insulate the stranded cables with extruded unpigmented TFE Teflon to give a maximum diameter of 0.030 inch over the insulation. Also required was that the insulated cables conform to military Specification MIL-W-16878-D Type ET.

The methods used by Philadelphia to apply the Teflon insulation to the experimental lead wires were the same methods used to insulate silver-plated copper lead wires. Briefly, the method consists of forming cylindrical extrusion blanks by compacting raw Teflon and lubricant, extruding this mixture onto the cable, heating the extruded insulation to volatilize lubricant, and curing the Teflon.

While the actual time-temperature cycles used by the Philadelphia Wire Company to cure Teflon are proprietary, the wires are estimated to reach 450 F for times of about 1/2 minute, during volatilization of lubricant from the Teflon, and are estimated to reach 650 F for times less than 2 minutes during curing of the Teflon. Since these thermal treatments and possible reaction with by-products of Teflon curing or reaction with the air atmosphere in the curing ovens can affect the mechanical properties of lead wire materials, the effects of Teflon curing on the properties of the silver materials were studied. Results of this investigation are discussed in a later section of this report.

The successful extrusion of Teflon onto the cables requires that the stranded cables be uniform in diameter and that no discontinuities, such as a kink in an outermost strand, occur. Philadelphia reported that the stranded cables of the silver alloys were uniform in diameter and had no defects in the outer strands. Accordingly, no unusual difficulties were encountered during coating with Teflon.

Observations Regarding Teflon-Insulated Cables

The appearances of the insulated 19/42 cables of the scaled-up alloys, viewed on spools, is described below.

Both the pure silver and Alloy B appeared white viewed through the Teflon. However, some tarnished areas were evident and are attributed by the Philadelphia Wire Company to the presence of residual drawing lubricant during the Teflon curing.

Alloys A and C, containing copper, were slightly oxidized during Teflon curing and appear light gold in color. Alloy C (partially annealed) is lighter than Alloy A; Alloy C (fully annealed) is even lighter, being almost white. Significantly, the golden tints on the alloys with copper are uniform in color over the wire surfaces. There are no red spots that might lead NASA inspectors to reject the wires because of suspected "red plague".

As discussed in the laboratory studies, the golden colors on the copper-containing alloys probably resulted from the oxidation of microscopic copper-rich areas when the materials were heated in air to cure the Teflon. That Alloy C (fully annealed) was nearly white confirmed results of the laboratory studies which showed that the golden color can be minimized in Alloy C by heating it to sufficiently high temperatures to dissolve the copper-rich phase. The laboratory studies have shown that the presence of the golden oxide does not affect solderability of the alloys. Other possible effects of oxide on the performance of lead wires in slip rings remain to be evaluated by NASA.

During flexure-breakage studies on the Teflon insulated cables, strands in some specimens were found to be slightly bonded together. While these bonds degraded the flexibility of the cables, the bonds were not so firm that individual strands could not be separated from within the bonded regions. More bonded areas were found in cables of pure silver and Alloy B than in cables of Alloys A and C, although a few bonded sections were also discovered in these latter cables.

Since, according to the Hudson Wire Company, no strands were bonded in the stranded-annealed cables, the bonding evidently occurred during application and curing of the Teflon. Personnel at the Poly-Scientific Corporation, who have extensive experience with slip-ring lead wires of silver-plated copper, suggest that bonding of strands during insulation results from excessive exposure times at the Teflon curing temperature. They have observed that bonding of strands occurs near the ends of cables since the cables are slowed, moving through the curing oven, as the cable end approaches. Less likely because of accurate temperature control, fluctuations of temperature profiles in the ovens during curing of the Teflon might also produce bonding of strands.

Battelle suggests that bonding of strands during Teflon curing may occur because (1) the wire strands are compressed into intimate contact with one another by the Teflon sheath and (2) that halide by-products of Teflon curing may create chemically active wire surfaces that promote bonding during the thermal exposure. The copper-containing alloys are possibly not as subject to bonding as pure silver and Ag-0.2 Ni because the oxide film formed on Ag-Cu and Ag-Cu-Ni alloys prevents the formation of chemically active surfaces.

Since the scaled-up cables were Teflon insulated using identical procedures, curing temperatures, etc, to those used by the Philadelphia Wire Company to insulate silver-plated copper lead wires for NASA (Poly-Scientific Corporation), bonding of strands in the scaled-up alloys is not expected to have occurred in the overall wires to a greater extent than the usual bonding observed in the silver-plated copper.

Inventory of Teflon-Insulated Lead Wire Produced at the Philadelphia Wire Company

The Teflon-insulated cables were inspected by the Philadelphia Wire Company and only the portions of cable that had dielectric integrity at 2400 v a-c, that had a diameter less than 0.030 inch, and that met requirements of MIL-W-16878-D Type ET were accepted for further study.

Fifty feet of insulated cable from each of the scaled-up silver materials was retained by Battelle for evaluation. The remaining portions were shipped to Mr. Estel G. Lowe of NASA, on July 19, 1966, for evaluation in slip-ring assemblies. An inventory of the cables shipped to NASA is given in Table 21. As shown in Table 21, each total length of cable consists of several pieces. These pieces resulted when sections of the cable, not meeting specifications, were removed.

During production of the 19/42 cables at the Hudson Wire Company, four resistance welds were made in Alloy B and one weld in Alloy C (partially annealed) to obtain optimum lengths for Teflon insulation. These weld regions were marked with brown ink which was not obliterated during application and curing of the Teflon. The number of welds remaining in the wires shipped to NASA is unknown. However, these welds should be identifiable by the ink marking.

EVALUATION OF SLIP-RING LEAD WIRES

Properties of Materials Before Being Insulated With Teflon

Full-Hard, As-Stranded Condition

Tensile properties and electrical conductivities of the 19/42 as-stranded cables are given in Table 22. As shown in Table 22, the alloys had very high strengths, low elongations, and reduced electrical conductivities, characteristic of their full-hard condition. On the other hand, the pure silver cable had low strength, moderate elongation, and high electrical conductivity, not characteristic of the wrought condition. Apparently, the pure silver was partially annealed during the final drawing operations as a result of frictional heating from contact with the dies. Severely cold worked silver of high purity is known to anneal at temperatures near 150 F – a temperature which the wire could have reached during the drawing operation.

Stranded, Annealed Condition

Properties determined by the Hudson Wire Company on the 19/42 cables and on single 42-gage strands in the stranded, annealed conditions are compared in Table 23 with the properties specified by Battelle. As shown in Table 23, Hudson produced the specified ultimate strengths and elongations in the alloys. However, the elongation of the pure silver cable was below the desired target. Evidently the self annealing of the pure silver reduced its elongation. Hudson was not equipped to measure the yield strengths.

TABLE 21. INVENTORY OF 19/42 TEFLON-INSULATED LEAD WIRES PRODUCED FOR NASA FROM THE SCALED-UP ALLOYS

Wire	Spool	Total Length of Cable, feet	Number of Pieces on Spool	Length of Individual Pieces, feet
Pure Silver	1	3,600	6	1,485, 320, 220, 270, 1,225, 80
	2	1,490	3	485, 445, 560
Alloy A	3	3,215	12	570, 230, 270, 130, 185, 85, 100, 30, 525, 445, 355, 290
	4	1,690	4	415, 1,170, 80, 25
Alloy B	5	1,990	6	1,195, 135, 180, 270, 30, 180
	6	3,395	10	200, 1,115, 70, 310, 675, 150, 280, 380, 110, 105
Alloy C, partially annealed	7	3,270	11	575, 545, 155, 340, 135, 265, 140, 70, 150, 785, 110
Alloy C, fully annealed	8	1,725	4	170, 250, 180, 1,125
	9	3,580	8	310, 1,310, 140, 255, 95, 1,050, 360, 60

TABLE 22. PROPERTIES OF 19/42 CABLES IN THE AS-STRANDED CONDITION[(a)]

Wire	Ultimate Tensile Strength, ksi	Elongation, in 10 Inches, percent	Electrical Conductivity, at 74 F, percent IACS
Pure silver	23.6	12	102
Alloy A	81.5	1	85.9
Alloy B	60.8	1	93.9
Alloy C	68.8	1	85.1

(a) All materials were stranded in the full hard (94 percent RA) condition.

TABLE 23. PROPERTIES OF SCALED-UP CABLES IN THE STRANDED, ANNEALED CONDITIONS[a]

Wire	Strand Annealing Temperature, F	Properties Determined by the Hudson Wire Company: Ultimate Strength, ksi: Single 42-Gage Strand	Ultimate Strength, ksi: 19/42 Cable	Elongation in 10 Inches, percent: Single 42-Gage Strand	Elongation in 10 Inches, percent: 19/42 Cable	Electrical Conductivity at 73 F, percent IACS: 19/42 Cable	Properties Desired by Battelle: Minimum Ultimate Strength, ksi	Range of 0.2 Percent Yield Strength, ksi	Minimum Elongation in 10 Inches, percent
Pure silver	700	26.4	24.3	14	17	102	25	7-12	24
Alloy A	950	35.1	34.9	22	30	93.8	30	8-13	24
Alloy B	800	31.8	31.2	22	25	102	29	9-14	20
Alloy C, fully annealed	1050	33.9	32.2	23	26	93.8	31	11-16	24
Alloy C, partially annealed	850	36.3	36.4	14	16	93.4	32	20-25	15

(a) Wires were stranded full hard and were subsequently strand annealed in a 4-foot-long oven at a rate of 100 feet per minute.

Also shown in Table 23 is that the strengths of single 42-gage strands removed from the cables were slightly higher than for the cables, while the elongations of single strands were slightly lower.

Average tensile properties determined at Battelle on the stranded, annealed cables and on single 42-gage strands removed from the cables are given in Table 24. Complete tensile results are given in Appendix D, Table D-3. Comparison of the properties in Table 24 with the properties in Table 23, determined by the Hudson Wire Company, shows good agreement between the ultimate strength values but less agreement between values of elongation. In particular, the elongation of 19/42 cable of pure silver is thought to be about 9 percent, not 17 percent and the elongation of 19/42 cable of Alloy A is thought to be about 19 percent rather than 30 percent as reported by Hudson.

As shown in Table 24, the yield strengths of the alloys and pure silver significantly exceeded the range specified by Battelle. However, the high yield strengths are not expected to significantly affect the behavior of lead wires.

TABLE 24. TENSILE PROPERTIES ON ANNEALED SCALED-UP ALLOYS BEFORE BEING INSULATED WITH TEFLON

	Ultimate Tensile Strength, ksi		0.2 Percent Offset Yield Strength, ksi		Elongation in 10 Inches, percent	
Wire	Single 42-Gage Strand	19/42 Cable	Single 42-Gage Strand	19/42 Cable	Single 42-Gage Strand	19/42 Cable
Pure silver	24.6	23.3	16.2	16.1	15.5	8.8
Alloy A	35.5	35.3	28.2	29.4	17.3	19.0
Alloy B	31.4	30.8	21.6	18.9	18.1	22.3
Alloy C, fully annealed	33.4	33.4	24.8	24.4	20.4	26.2
Alloy C, partially annealed	36.9	36.7	30.7	31.1	10.9	18.3

Flexure-breakage properties of the 19/42 cables, before being insulated, are given in Table 25. Specimens were tested on Battelle's flexure-breakage apparatus, which has been used throughout this program. During testing, specimens were bent over a 0.025-inch radius with a tensile load of 200 grams hanging on the wires. Rupture of the first strand in the cables was detected by an abrupt change in the electrical resistance of the cable.

As shown in Table 25, Alloy C in the partially annealed temper had the longest flexure-breakage life, 85 bend cycles to rupture the first strand and 134 cycles to rupture the entire cable. Alloys A and C (fully annealed) had very similar flexure-breakage lives. Alloy B had a life to rupture the first strand nearly as long as for

TABLE 25. FLEXURE-BREAKAGE PROPERTIES OF ANNEALED 19/42 CABLES BEFORE BEING INSULATED WITH TEFLON[a]

Wire	Specimen	Bend Cycles to Rupture First Strands	Bend Cycles to Rupture the Cable
Pure silver	1	27	41
	2	24	45
	3	27	49
	4	33	40
	5	24	39
	6	31	42
Average		28	43
Alloy A	1	67	86
	2	66	94
	3	50	85
	4	45	95
Average		57	90
Alloy B	1	41	64
	2	55	65
	3	56	70
	4	55	70
Average		52	67
Alloy C, fully annealed	1	48	85
	2	60	88
	3	54	97
	4	72	97
Average		59	92
Alloy C, partially annealed	1	90	119
	2	77	133
	3	87	144
	4	82	143
	5	87	130
Average		85	134

(a) Cables were bent through an angle of 95° over a 0.025-inch radius while supporting a 200-gram load. Tests were conducted at a rate of 6 bend cycles per minute (a cycle is a bend through 95° and return to 0°).

Alloys A and C (fully annealed), but the life of the total cable of Alloy B was about 23 bend cycles less than that of the other alloys. Pure silver had the lowest flexure-breakage life, 28 bend cycles to rupture the first strand and 43 cycles to complete failure.

Properties of Materials After Being Insulated With Teflon

Studies on Wires With Teflon Insulation Removed

The tensile properties of 19/42 cables of the scaled-up materials, tested with the insulation removed, are given in Table 26 and in Appendix D, Table D-3. As shown in Table 26, the three alloy wires have ultimate strengths exceeding NASA's target of 30 ksi. The pure silver wire, on the other hand, has low strength. In fact, its strength is below that generally expected for pure silver, about 24 ksi; furthermore, the elongation is much below the value expected, about 45 percent. These reduced properties in the pure silver are thought to be the result of irregular grain growth. When very pure silver that has been slightly cold worked is annealed, some of the wrought structure recrystallizes to form very small grains, while other grains in relatively strain-free regions grow to large sizes. These large grains may in fact approach diameters near that of the wire. When specimens containing these very large grains, in a structure with small grains, are tested in tension, they often fail with low strengths and reduced elongations as a result of sliding of the large grains over one another to produce fracture.

TABLE 26. TENSILE PROPERTIES OF THE SCALED-UP MATERIALS WITH TEFLON INSULATION REMOVED

Wire	Ultimate Tensile Strength, ksi		0.2 Percent Offset Yield Strength, ksi		Elongation in 10 Inches, percent	
	Single 42-Gage Strands	19/42 Cable	Single 42-Gage Strands	19/42 Cable	Single 42-Gage Strands	19/42 Cable
Pure silver	22.3	18.7	17.4	12.8	5.2	13.4
Alloy A	35.1	33.2	26.1	26.2	20.3	16.5
Alloy B	30.4	29.7	20.9	19.4	19.0	28.3
Alloy C, fully annealed	33.4	33.0	24.2	28.4	21.2	28.4
Alloy C, partially annealed	35.8	35.3	30.1	30.1	14.0	18.5

The results of flexure-breakage tests on 19/42 cables of the scaled-up alloys, tested with the Teflon removed, are given in Table 27. Alloy C in the partially annealed condition had slightly longer flexure breakage lives than in the fully annealed

TABLE 27. FLEXURE-BREAKAGE PROPERTIES OF 19/42 CABLES WITH TEFLON INSULATION REMOVED

Wire	Specimen	Band Cycles To Rupture First Strands	Band Cycles To Rupture The Cable
Pure Silver	1	36	47
	2	32	45
	3	26	34
	4	20	29
	Average	29	39
Alloy A	1	43	91
	2	52	92
	3	44	85
	4	36	86
	Average	44	89
Alloy B	1	28	44
	2	30	61
	3	30	52
	4	32	46
	Average	30	51
Alloy C, fully annealed	1	53	86
	2	62	87
	3	40	89
	4	50	80
	Average	51	86
Alloy C, partially annealed	1	42	88
	2	65	102
	3	71	126
	4	44	110
	5	44	86
	Average	53	102

(a) Cables were bent through an angle of 95° over a 0.025-inch radius while supporting a 200-gram load. Tests were conducted at a rate of 6 bend cycles per minute (a cycle is a bend through 95° and return to 0°).

condition. Both conditions of Alloy C had longer lives than the other materials. As shown in Table 27, Alloy A had a longer flexure breakage life than Alloy B, while Alloy B had longer life than pure silver. More scatter was observed in the flexure-breakage results on the cables tested after they were insulated with Teflon. This scatter is thought to have occurred because strands in some of the bend specimens were bonded together during the Teflon-curing treatment. Specimens with reduced flexibility, as a result of bonded strands, had lower flexure-breakage lives than specimens that contained free strands.

Studies on Cables With Teflon Insulation

Properties of cables of the scaled-up materials were also evaluated with the Teflon insulation in place. The effect of the insulation on the tensile properties of the alloy wires is summarized in Table 28. (Tensile tests were stopped after all 19 wire strands had broken. The Teflon was intact.) Complete tensile-test results are given in Appendix D, Table D-4. As shown in Table 28, the presence of Teflon on the stranded wires greatly improved their elongations and also produced significant increases in ultimate strengths and yield strengths. In fact, the ultimate breaking loads for the alloy wires within the insulated cables were within 0.05 pound of one another even though the differences in ultimate strengths of the uninsulated alloys have been shown to be more pronounced. The ultimate breaking load for insulated pure silver wires was only 16-17 percent less than for the alloys although the ultimate strength of the pure silver metal was up to 38 percent inferior to that of the alloys.

TABLE 28. EFFECT OF TEFLON INSULATION ON THE TENSILE PROPERTIES OF THE SCALED-UP ALLOYS

	Properties of Wires Tested with Teflon			Comparison of Properties of Wires Tested With and Without Teflon, Increase Produced by Teflon		
Wire	Ultimate Breaking Load, pounds	Load at 0.2 Percent Offset Yield Strength, pounds	Elongation in 10 Inches, percent	Ultimate Breaking Load, pounds	Load at 0.2 Percent Offset Yield, Strength, pounds	Elongation in 10 Inches percent
Pure silver	4.12	1.56	34.9	2.09	0.37	21.5
Alloy A	4.95	2.86	42.0	1.86	0.42	35.5
Alloy B	4.98	2.09	54.3	2.21	0.18	25.7
Alloy C, fully annealed	5.00	2.53	49.9	1.92	0.29	21.5
Alloy C, partially annealed	4.95	3.10	36.0	1.76	0.29	17.5

These observed increases in strength and elongation imparted to the 19/42 cables by the Teflon insulation should further increase the resistance of the lead wires to failure as a result of being overstressed. The tendency of the Teflon to equalize the ultimate strengths of the cables, regardless of the alloy wire strengths, cannot be explained from the limited data accumulated during these studies on the composite cables. On the other hand, the large increases in elongation imparted to the alloy wires by Teflon most probably occurred because the Teflon effectively distributed the applied stress over the 19 strands and, consequently, inhibited the onset of fracture. All 19 strands within Teflon insulation ruptured at the same time while strands in uninsulated cables ruptured sequentially.

The electrical properties of the finished lead wires are given in Table 29 and Appendix D, Table D-5. As shown in Table 29, all the scaled-up materials have electrical conductivities above the target value of 90 percent IACS.

TABLE 29. ELECTRICAL PROPERTIES OF THE FINISHED LEAD WIRES FABRICATED FROM THE SCALED-UP ALLOYS

Wire	Specific Electrical Resistivity, microohm-cm		Electrical Conductivity, percent IACS	
	Single 42-Gage Strand	19/42 Cable	Single 42-Gage Strand	19/42 Cable
Pure Silver	1.68	1.67	103.2	103.4
Alloy A	1.77	1.81	97.4	95.1
Alloy B	1.73	1.69	99.9	101.7
Alloy C, fully annealed	1.83	1.82	94.6	94.9
Alloy C, partially annealed	1.82	1.82	94.8	94.9

The flexure-breakage behavior of the finished, insulated cables was also evaluated. During these studies, the rupture of the first wire strand could be detected by an abrupt change in the electrical resistance of the specimen but the resistance change produced by rupture of the 19th strand was not discernible. Thus, tests were stopped after the resistance changes indicated that many strands had ruptured. The insulation was carefully removed and the broken strands were counted.

In addition to determining the number of bend cycles to rupture stranded, insulated wires, the effect of bend cycles on the electrical resistance of wires was determined. This evaluation was expected to yield results that are possibly more significant to lead-wire applications than merely determining the flexure-breakage life.

Results of the flexure tests on finished, Teflon-insulated lead wires are given in Table 30. As shown in Table 30, Alloy C in the partially annealed temper appears to have the greatest flexure-breakage life among the scaled-up materials. One specimen of Alloy C (partially annealed) endured 150 bend cycles (300 bends) with no strand failures; another specimen endured 324 bend cycles (648 bends) with only one strand broken. Another specimen of Alloy C, however, had 15 broken strands after 60 cycles (120 bends).

As suggested by the data in Table 30, Alloy A may have greater flexure-breakage life than Alloy C in the fully annealed condition. The differences were not great. The flexure life of Alloy B is somewhat greater than the life of pure silver.

TABLE 30. FLEXURE-BREAKAGE BEHAVIOR OF TEFLON-INSULATED LEAD WIRES[(a)]

Wires	Specimen	Cycles To Rupture First Strands	Cycles at End of Test	Number of Ruptured Strands	Resistance[(b)] Change in 4 Inches at End of Test, milliohms
Pure silver	1	30	54	16	0.7
	2	30	54	15	0.5
	3	27	53	15	0.7
	4	27	55	16	0.3
	5	30	62	19	0.7
Alloy A	1	78	102	19	1.3
	2	54	78	17	0.3
	3	36	69	16	0.5
	4	54	116	19	1.0
	5	66	104	16	0.6
Alloy B	1	36	54	17	0.6
	2	27	40	6	0.2
	3	24	48	6	0.4
	4	32	71	18	0.7
Alloy C, fully annealed	1	42	60	17	0.5
	2	45	48	7	0.8
	3	45	79	18	0.9
	4	48	99	17	0.3
	5	41	93	18	0.9
Alloy C, partially annealed	1	78	102	6	0.4
	2	—	150	0	0.2
	3	240	324	1	0.2
	4	48	60	15	1.2
	5	48	84	16	0.6

(a) Cable specimens were bent through an angle of 95° over a 0.025-inch radius while supporting a 200-gram load. All tests were conducted at a rate of 6 bend cycles per minute (a cycle is a bend through 95° and return to 0°).

(b) Resistance of cables was calculated from the voltage drop through 4 inches of cable produced by a current of 15×10^{-3} amperes flowing through the specimen.

Also shown in Table 30 is that scatter in the flexure-breakage results is considerable, particularly for tests on Alloys A and C. Since the test conditions - bend radius, load, bend rate, and current-flowing in the specimens - were the same for all tests, the scatter is believed to have resulted from differences in the specimens. That is, the sticking together of strands in some specimens is thought to be primarily responsible for the scatter. Less scatter was observed for pure silver and Alloy B because all specimens contained some bonded strands. On the other hand, some specimens of Alloys A and C had some bonded strands while, in other specimens, no strands were bonded together.

Monitoring the electrical resistance of specimens during the bend tests showed that the resistance increase in a 4-inch length of insulated lead wire was less than 1×10^{-3} ohms until rupture of the first strands, for all the scaled-up materials. Rupture of the first strands produced a resistance increase of about 0.3×10^{-3} ohms over a 4-inch specimen length, for all the materials. The resistance continued to increase as strands ruptured although the broken ends, constrained within the Teflon, made electrical contact when the specimen was straight in the bend cycle. When the specimen was in the bend configuration, the maximum resistance increase due to ruptured strands was observed. This behavior produced a sawtooth pattern on the voltage drop versus time curve during the bend tests. Values of the maximum resistance increase produced by rupture of numerous strands in the cables are also given in Table 30. As shown in Table 30, these resistance increases ranged from about 0.7 to 1.3 milliohms when 18 or 19 strands were ruptured.

Following rupture of all 19 strands, open circuits did not result. Rather, the Teflon held the broken ends in contact. As bend tests were continued on the specimens with all strands broken, the elongation of Teflon within the bend region separated the wire ends, further increasing the specimen resistance. Significantly, elongation of the Teflon after 540 bend cycles (1080 bends) did not separate the broken wire ends a sufficient distance to produce an open circuit. The bend cycles to produce open circuit in the wires and rupture of the Teflon was not determined.

Effect of Teflon-Curing Cycle on the Properties of Scaled-Up Alloys

The effect of the Teflon-curing cycle on the mechanical properties of the scaled-up lead wires was studied to determine if the properties of the silver materials were altered by the thermal treatment or as a result of oxidation or chemical reaction with the Teflon by-products. Only the thermal conditions of the Teflon-curing cycle could be simulated during preliminary alloy-development studies.

The effects of the Teflon-curing treatment on the properties of the scaled-up alloys are summarized in Table 31. As shown in Table 31, the Teflon-curing cycle did not significantly alter the tensile properties of the alloys or of pure silver. The slight decreases in strengths resulted from annealing effects during the thermal exposure. The improvements in elongation for the alloys attending the slight strength losses show that the alloys were not degraded by oxidation or chemical reaction during Teflon curing. The loss of elongation in the pure silver cable is speculated to be the result of irregular grain growth. This type of grain growth can occur in very pure silver that has been slightly cold worked before recrystallization. Self annealing during wire drawing, as was reported by Hudson Wire Company on the basis of tensile properties for the pure silver cable, could have led to this irregular type of grain growth during stranding and subsequent thermal treatments.

TABLE 31. EFFECT OF TEFLON-CURING CYCLE ON THE MECHANICAL PROPERTIES OF THE SCALED-UP ALLOYS

Wire	Change in[a] Ultimate Tensile Strength, ksi	Change in[a] 0.2 Percent Offset Yield Strength, ksi	Change in[a] Elongation in 10 Inches, percent	Change in Flexure-Breakage Properties of 19/42 Cables: Cycles to Rupture First Strand	Change in Flexure-Breakage Properties of 19/42 Cables: Cycles to Rupture Cable
Pure silver	-1.0	-0.2	-3.6	+1	-4
Alloy A	-0.2	-3.3	+1.4	-13	-1
Alloy B	-1.0	-0.7	+0.9	-22	-16
Alloy C, fully annealed	0	-0.6	+0.8	-8	-6
Alloy C, partially annealed	-1.1	-0.6	+3.1	-32	-32

(a) Determined from test results on 42 gage strands without Teflon insulation.

Also shown in Table 31 is that the flexure-breakage lives of the alloys were significantly lower after Teflon curing than before. Since the changes in the mechanical properties of the materials during Teflon curing were small, this loss of flexure-breakage life is suspected to have been caused by bonding of strands in the cables, rather than by changes produced in the metals.

Properties of Silver-Plated Copper Lead Wires

Flexure-Breakage Properties

Specimens of the 19/42 cable of silver-plated copper currently used in NASA slip-ring devices were flex tested in the Battelle device to obtain flex-life data that could be compared with the flex data on the experimental silver alloys. This comparison is useful to predict the relative reliability of the silver-alloy lead wires, during flexing.

The specimens of silver-plated copper were tested using the same conditions used to evaluate the silver alloys - 200 gram load, 0.025-inch head radius, 6 bend cycles per minute.

Results of the flexure tests on the silver-plated copper are given in Table 32. Comparison of the flexure-life data for the silver alloys given in Tables 27 and 30 with the data in Table 32 shows that Alloys A, B, and C have longer flexure-breakage lives than silver-plated copper. Although the pure silver cable had flexure-breakage lives below the lives for silver-plated copper, the differences were slight.

The most vivid comparisons of flexure-breakage life of the metals for purposes of selecting superior cable alloys can be obtained by comparing the flex data for cables tested after the insulation is carefully removed. Such a comparison eliminates influence of the Teflon insulation such as variations in Teflon adherence along the cable length. Comparison of flex data for the bare cables of the silver alloys and silver-plated copper, Tables 27 and 32, shows the following:

Wire	Bend Cycles to Rupture First Strand, Percent Compared With Silver-Plated Copper	Bend Cycles to Rupture All 19 Strands, Percent Compared With Silver-Plated Copper
Pure silver	94	93
Alloy A	142	212
Alloy B	97	120
Alloy C, fully annealed	165	204
Alloy C, partially annealed	171	243

Alloys A and C have 1.4 to 1.7 times the flexure life of silver-plated copper to rupture the first strand and have total lives for rupture of all strands 2.1 to 2.4 times the life of silver-plated copper. Therefore, the use of lead wires from silver Alloys A or C should result in significantly increased resistance to flexure breakage.

TABLE 32. FLEXURE-BREAKAGE RESULTS ON 19/42 CABLE OF SILVER-PLATED COPPER(a)(b)

Specimen Condition	Specimen	Bend Cycles to Rupture First Strands	Cycles at End of Test	Number of Strands Ruptured
Insulation removed	1	27	40	19
	2	33	45	19
	3	33	42	19
Average		31	42	
With Teflon insulation	1	30	42	19
	2	34	54	14
	3	36	63	17
Average		33		

(a) Specimens were tested on the Battelle flexure-breakage device using the same test conditions (95° bend over 0.025-inch radius while supporting a 200-gram load) used to test the experimental silver-alloys.

(b) The 19/42 Teflon-insulated cable of silver-plated copper was supplied, free of charge, by the Philadelphia Insulated Wire Company. According to personnel at Philadelphia, the wire supplied is a representative sample of the silver-plated copper lead wires used by NASA in slip-ring devices.

Tensile Properties

The tensile properties of silver-plated copper lead wires, tested with the Teflon insulation removed, were also determined for comparison with the properties of the solid-silver materials. Results of the tensile tests on the 19/42 cable of silver-plated copper are given in Table 33.

TABLE 33. TENSILE PROPERTIES OF 19/42 SILVER-PLATED COPPER TESTED WITH THE TEFLON INSULATION REMOVED

Specimen	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 10 Inches, percent
1	33.4	24.1	26.2
2	33.4	24.1	24.6
3	33.4	23.9	26.2
Average	33.4	24.0	25.6

Comparison of the tensile properties of the scaled-up silver alloys, given in Table 26, with the properties of silver-plated copper, given in Table 33, shows that Alloy C (partially annealed) has higher strengths than silver-plated copper but has a lower elongation. Alloys A and C (fully annealed) have the same ultimate strength as silver-plated copper and have higher yield strengths. Alloy C (fully annealed) also has a higher elongation than silver-plated copper. However, the elongation of Alloy A is below the value for silver-plated copper. Alloy B has lower strengths than silver-plated copper but has higher elongation. The strengths and elongation of the scaled-up pure silver cable are inferior to the properties of silver-plated copper.

DISCUSSION OF RESULTS AND CONCLUSIONS

The screening study of 30 silver alloys yielded three alloys for lead-wire construction that are expected to significantly improve the reliability of slip-ring devices. These alloys (scale-up Alloys A, B, and C) were readily fabricated to 19 strand, 42 gage cable and were insulated with extruded Teflon, demonstrating their ability to be manufactured to the construction desired for NASA slip-ring lead wires. The alloys further met all the properties desired of lead-wire materials except the ability to withstand at least 400 bends over a 0.025-inch radius while supporting a 200-gram load. Nevertheless, the silver-alloy lead wires withstood as many as 2.4 times as many bends to failure as the silver-plated copper lead wires currently used in slip-ring devices.

All three of the scaled-up silver alloys, as well as pure silver, have excellent corrosion resistance. No corrosion was detected on specimens during 1,512 hours of alternate immersion in a water-2 percent hydrofluoric acid-5 percent sodium fluoride solution. This environment is thought to be much more corrosive than conductors would encounter within Teflon insulation.

All the scaled-up materials were readily solderable. Alloys B and C were also judged readily weldable by the Hudson Wire Company. Alloy A and pure silver were not welded but should similarly be very weldable.

Property studies on alloy wires after insulation revealed that all the alloys are compatible with TFE Teflon during the curing cycle. No loss of properties occurred by reaction with Teflon decomposition products or by reaction with air.

Based on the results of this program, Alloy C (Ag-1 Cu-0.2 Ni), in the partially annealed condition, appears to be the best lead-wire candidate among the silver alloys studied. This alloy/condition offers an ultimate strength of 35 ksi, a yield strength of 30 ksi, and an elongation of 19 percent. Its electrical conductivity is 95 percent IACS and its flexure-breakage life (102 cycles to rupture 19 strands) was significantly longer than for the other silver alloys. A possible disadvantage of the partially annealed condition is that a light gold colored oxide (visible only when the wire is viewed on the spool) forms on the wire during Teflon curing. While this oxide does not degrade mechanical properties or impair solderability, it may impair electroplating of other metals onto the conductor. On the other hand, this very thin oxide may be beneficial in preventing "wicking" of solder up the insulation. This "wicking" phenomenon decreases the flexibility of lead wires near soldered joints. Also, much less bonding of strands occurred in Alloys A and C than in pure silver and Alloy B cables during Teflon curing. Most probably, the oxide film on A and C conductors acted as a barrier to bonding. This condition is desirable since bonding of strands significantly lowers the flexure breakage life.

The fully annealed condition of Alloy C ranks as the second best lead-wire candidate. This temper has an ultimate strength of 33 ksi, a yield strength of 24 ksi, and an excellent elongation of 28 percent. It has an electrical conductivity of 95 percent IACS and a flexure-breakage life of 86 cycles to complete failure of 19 strands. A possible advantage of the fully annealed temper over the partially annealed temper is that the fully annealed condition does not form as noticeable an oxide during Teflon curing.

Alloy A (Ag-1.5 Cu), fully annealed, has nearly equivalent strengths, flexure-breakage life, and electrical conductivity to Alloy C in the fully annealed temper but has a significantly lower elongation. Also, Alloy A is more susceptible to the formation of a golden-colored surface oxide during Teflon curing than either condition of Alloy C. Therefore, Alloy A is ranked as the third best candidate for lead wires.

Alloy B (Ag-0.2 Ni) just meets the strength requirement with an ultimate strength of 30 ksi. It has a yield strength of 21 ksi combined with an excellent elongation of 28 percent. Also outstanding is its electrical conductivity of 102 percent IACS. The flexure-breakage life of Alloy B, however, is significantly below the lives for Alloys C and A, with rupture of 19 strands occurring at 51 cycles. Alloy B, without copper, does not form a surface oxide during Teflon curing. This alloy is ranked fourth among the alloy candidates because of its lower strengths and flex life.

All three of the silver alloys offer significantly greater strengths and flexure-breakage lives than pure silver. While the 19/42 cable of pure silver produced during this program did not have optimum properties for silver, particularly elongation, the best strength and flexure-breakage lives possible with pure silver will most certainly be significantly inferior to the alloy properties.

Comparison of the mechanical properties of the silver materials with those of silver-plated copper has shown that all of the silver alloys have significantly greater resistance to flexure breakage than silver-plated copper. Furthermore, Alloys A and C have higher strengths than silver-plated copper, while Alloy B has somewhat lower strength. Thus, use of silver Alloys A or C to replace silver-plated copper lead wires will not only eliminate the threat of "red plague" but should also give increased resistance to lead-wire failures due to mechanical breakage.

Monitoring the electrical resistance of insulated lead wires during flexure-breakage tests showed that the electrical resistance of the conductors only increases about 1 milliohm when all 19 strands rupture. Thus, rupture of lead wires in areas covered with Teflon would probably not affect the performance of the lead wire, unless the tensile stress on the wire was sufficient to pull the conductor ends apart.

RECOMMENDATIONS

Alloy C (Ag-1 Cu-0.2 Ni) in the partially annealed temper has been shown to have the best combination of lead wire properties among the experimental silver alloys studied. Accordingly, Battelle recommends that NASA evaluate this composition in slip-ring devices. Of particular interest in the evaluation would be the effects on lead-wire performance of the thin oxide formed on the conductors. If the presence of the oxide proves undesirable, Battelle recommends Alloy C in the fully annealed temper as the best lead-wire candidate. Although the lead wire prepared from fully annealed Alloy C during this program appears to have a thin oxide on the surface of conductors, it was demonstrated during laboratory studies that this alloy can be prepared so that it will not form a visible oxide. This oxidation-resistant condition is produced by annealing the alloy at a sufficiently high temperature to dissolve the copper-rich phase. Therefore, the alloy should be annealed at a temperature above the 1050 F temperature used to prepare the alloy cable during this program. Annealing in the range 1100-1200 F is expected to produce the oxidation-resistant condition. (However, an investigation should be conducted to determine if strands bond during annealing of stranded cable at 1100-1200 F.) Annealing Alloy C cable in this temperature range should give an ultimate strength of about 32 ksi, a yield strength near 18 ksi, and an electrical conductivity of about 92 percent IACS. Most probably the elongation of the alloy will increase slightly from the 28 percent value for the 1050 F annealed condition and the flexure-breakage life should not be significantly altered. Thus, Alloy C, annealed at temperatures above 1050 F, should have significantly better lead-wire properties than Alloy B, which is immune to oxidation during Teflon curing.

If pure silver should be selected for lead wires, the silver stock should have lower purity than the 99.99 fine stock used to prepare the silver cable during this program. Use of 99.9 fine silver is recommended to prevent the self-annealing during wire drawing that apparently reduced the properties of the silver cable prepared during this program.

Flexure-breakage tests conducted during this program showed that bonding of strands within cables significantly reduced the flexure-breakage life of lead wires.

This bonding is thought to have occurred during the Teflon curing. Therefore, to maximize flexure-breakage life of lead wires, the Teflon-curing cycle should be altered, if possible, to prevent bonding of strands without producing undesirable effects on the Teflon insulation.

* * * * *

Data contained in this report can be found in Battelle Memorial Institute Laboratory Record Books Nos. 22721, 22913, 22932, and 22975.

RHE/DNW/ESB:ims

APPENDIX A

SURVEY OF COMMERCIAL SILVER ALLOYS

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SURVEY OF COMMERCIAL SILVER ALLOYS

Silver-alloy producers and manufacturers of electrical contacts were surveyed to determine if any commercial silver-base alloys would meet the requirements for slip-ring lead wire. A list of the companies contacted in the survey is given below:

Company	Location	Supplied Data
Handy and Harman Company	850 3rd Avenue New York 22, New York	Yes
Engelhard Industries American Platinum and Silver Division	231 New Jersey Railroad Ave. Newark 5, New Jersey	Yes
Metals and Controls Division of Texas Instruments	34 Forest Street Attleboro, Massachusetts	Yes
American Silver Company	36-11 Price Street Flushing, New York	Nothing available
J. M. Ney Company	Box 990 Hartford, Connecticut	Yes
Goldsmith Brothers, Inc.	900 W. 18th Street Chicago, Illinois	Nothing available (produce same alloys as Handy and Harman)
Hoover and Strong Company	119 W. Tupper Buffalo, New York	Nothing available
Derringer Metallurgical Corp.	Mundelein, Illinois	Nothing available
Leach and Garner Corporation	49 Pearl Street Attleboro, Massachusetts	No reply
Improved Seamless Wire Co.	775 Eddy Street Providence 5, Rhode Island	Nothing available
Gibson Electric Company	Delmont, Pennsylvania	Yes
International Silver Company	Meriden, Connecticut	Produce only sterling silver
United Wire and Supply	Elmwood Avenue Providence, Rhode Island	No reply

Of the several hundred silver alloys commercially available, only the Ag-1.5 Cu copper alloy appears potentially useful as a substitute for silver-plated copper lead wires.

The properties obtained in annealed and cold-worked wires of the Ag-1.5 Cu alloy are given in Table A-1.

As shown in Table A-1, the Ag-1.5 Cu alloy has excellent electrical conductivity, 97 percent IACS, combined with an ultimate strengthof 32,200 psi in the annealed condition. Thus, this Ag-Cu alloy readily meets the conductivity-strength requirements for slip-ring lead wire.

TABLE A-1. SELECTED PHYSICAL PROPERTIES OF COMMERCIAL SILVER-1.5 PERCENT COPPER WIRE IN THE ANNEALED AND COLD-WORKED CONDITIONS[a]

Amount of Cold Work, percent reduction in area	Electrical Conductivity, percent IACS	Ultimate Tensile Strength, psi	Elongation, in 2 Inches, percent
Annealed	97.0	32,200	43
9.8	96.3	35,700	26
20.3	95.3	41,300	8
36.1	94.0	47,200	5
49.7	92.9	50,400	5
60.0	92.5	54,000	4
68.6	91.7	56,600	4
75.4	91.0	59,200	4

(a) Data from Industrial Product Bulletin No. A-2, "Silver-Copper Alloys", Handy and Harman Company, New York, New York.

Also shown in Table A-1 is that the strength of the Ag-1.5 Cu alloy can be raised by cold work without lowering the electrical conductivity below 91 percent IACS. However, the ductility of the alloy is significantly reduced by cold reductions in area greater than about 10 percent.

No data are available on the resistance of the Ag-1.5 Cu alloy to breakage during cyclic bending or twisting. However, the annealed alloy has good ductility and on this basis would be expected to have good flexure-breakage properties. On the other hand, wires which have been cold worked by more than about 10 percent reduction in area have lower ductility and probably poorer flexure-breakage resistance.

Fabricability of the alloy is good, making possible reductions in area of 70 to 80 percent between intermediate annealing treatments.* Producers stated that the composition can be fabricated to 0.0025-inch-diameter wire, required for slip-ring lead wires.**

No data are available on the chemical compatibility of the Ag-1.5 Cu alloy with TFE Teflon.

The corrosion resistance of the Ag-1.5 Cu alloy has not been studied. However, projection from what is known about the corrosion of Ag-Cu alloys suggests that the Ag-1.5 Cu composition may be slightly attacked by the corrosion conditions present in

*Private communication with Mr. R. Currie of Engelhard Industries.
**Private communication with Mr. E. Konrad of Engelhard Industries.

Teflon-insulated lead wires. At room temperature, the presence of copper in solid solution in silver has little effect on the corrosion resistance. However, in alloys containing appreciably more than 0.3 percent copper, the presence of small areas of a less-noble copper-rich phase slightly lowers the corrosion resistance because of electrolytic effects.* Exposure of these types alloys to severe corrosion conditions such as elevated temperatures in the presence of a good electrolyte will produce some selective attack of the copper-rich areas.

Resistance of the Ag-1.5 Cu alloy to oxidation in air at temperatures around 600 F is moderately good. When heated to temperatures above 480 F, the alloy darkens due to the formation of cuprous oxide at copper-rich areas on the surface.** During prolonged exposure at temperatures above 500 F, the interdiffusion of oxygen may cause embrittlement of fine wires by selectively oxidizing internal copper-rich areas.

The Ag-1.5 Cu alloy is moderately resistant to softening at elevated temperatures. Exposure of annealed Ag-1.5 Cu wires to 650 F, as would occur during curing of the Teflon insulation, is expected to slightly lower the ultimate strength. Cold-worked wires would also soften but would not be expected to recrystallize completely.

*Metals Handbook, American Society for Metals, Vol. 1, 8th Edition (1961), p 1184.
**Private communication with Mr. R. Currie and Mr. E. Konrad of Engelhard Industries.

APPENDIX B

SURVEY OF ALLOYING EFFECTS

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SURVEY OF ALLOYING EFFECTS

Alloying effects from published information are discussed according to the solid solubility of the various elements in silver. References are listed at the end of Appendix B.

Generally, the greatest alteration of electrical conductivity and strength is produced by elements that are in solid solution. Insoluble elements have little effect on the strength and alter the electrical conductivity in linear proportion to the volume percent of alloy element present.

Insoluble elements are generally more effective in raising the recrystallization temperature and in inhibiting grain growth than solid-solution elements.

The extent of solid solubility of metallic elements in silver is given in Table B-1. Both the maximum solid solubility, generally occurring at elevated temperatures, and the solubility at lower temperatures are included in Table B-1 to show the tendency of alloy systems to precipitate alloy elements during an aging treatment. Such precipitation can significantly alter alloy conductivity, strength, and corrosion resistance.

All data on alloying effects are presented for annealed material and represent maximum electrical conductivity and minimum tensile strength. Also, values of specific electrical resistance are given rather than values of electrical conductivity. A specific resistance of 1.916×10^{-6} ohm-cm results in 90 percent IACS electrical conductivity.

Effects of Solid-Solution Elements on the Electrical Conductivity and Strength of Silver

Palladium, Gold

Both palladium and gold form a continuous series of solid solutions with silver. As shown in Figures B-1 and B-2, palladium increases the specific resistivity slightly more than gold, but is a more effective strengthener.[1]

All alloys in the silver-palladium and silver-gold systems have excellent ductility as shown in Figure B-2.

Cadmium, Zinc, Indium

About 43 percent of cadmium, 29 percent of zinc, or 21 percent of indium are soluble in solid silver. While cadmium and zinc alloys with silver are not age hardenable, silver-indium alloys can be strengthened by aging.[2]

As shown in Figures B-3 and B-4, additions of indium or zinc greatly increase the electrical resistivity of silver.[3-5] Likewise, cadmium significantly increases the resistivity but to a lesser extent, for equal alloy additions, than indium or zinc.

TABLE B-1. EXTENT OF SOLID SOLUBILITY OF METALLIC ELEMENTS IN SILVER

Element	Maximum Solid Solubility at Indicated Temperature, weight percent	C	Solid Solubility at Lower Temperature, weight percent	C
Al	6.0	610	2.34	200
As	6.3	595	3.0	300
Au	Complete		Complete	
B	Insoluble		Insoluble	
Ba	?	?	?	?
Be	0.3	~860	0.13	~760
Bi	5.1	~550	0.6	~190
Ca	?	?	?	?
Cd	42.6	500	43.2	300
Ce	?	?	?	?
Co	Nil	1200	Nil	1000
Cr	Nil	?	?	?
Cu	8.8	779	0.2	200
Fe	Nil	1600	Nil	1000
Ga	13	611	8	200
Ge	6.7	651	1	~270
Hg	52.4	276	~50	~100
In	21	693	20	300
Ir	Insoluble		Insoluble	
La	?	?	?	?
Li	~5.5	330	~5	25
Mg	8.5	759	7.5	300
Mn	31	987	7.7	300
Mo	?	?	?	?
Na	0.22	?	?	?
Ni	0.102	922	0.012	400
P	<0.026	?	?	?
Pb	5.2	600	0.65	~225
Pd	Complete		Complete	
Pr	?	?	?	?
Pt	~30	~950	~1	~600
Re	Insoluble		Insoluble	
Rh	Insoluble		Insoluble	
Ru	Slight	?	?	?
S	<0.05	?	?	?
Sb	8.0	703	6.2	300
Se	?	?	?	?
Si	Nil	?	?	?
Sn	12.5[a]	724	10.2	200
Sr	?	?	?	?
Ta	Insoluble		Insoluble	
Te	Nil		Nil	
Th	0.2-0.3	894	?	?
Ti	?	?	?	?
Tl	13.2	~550	4.2	~150
U	0.4	950	?	?
V	Insoluble		Insoluble	
W	Insoluble		Insoluble	
Zn	22.3	710	29	258
Zr	Nil		Nil	

(a) This binary system may be incorrect. The solubility limit may be considerably higher.

Source: Hansen, M. and Anderko, K., Constitution of Binary Alloys, Second Edition, McGraw-Hill Book Company, Inc., New York (1958).

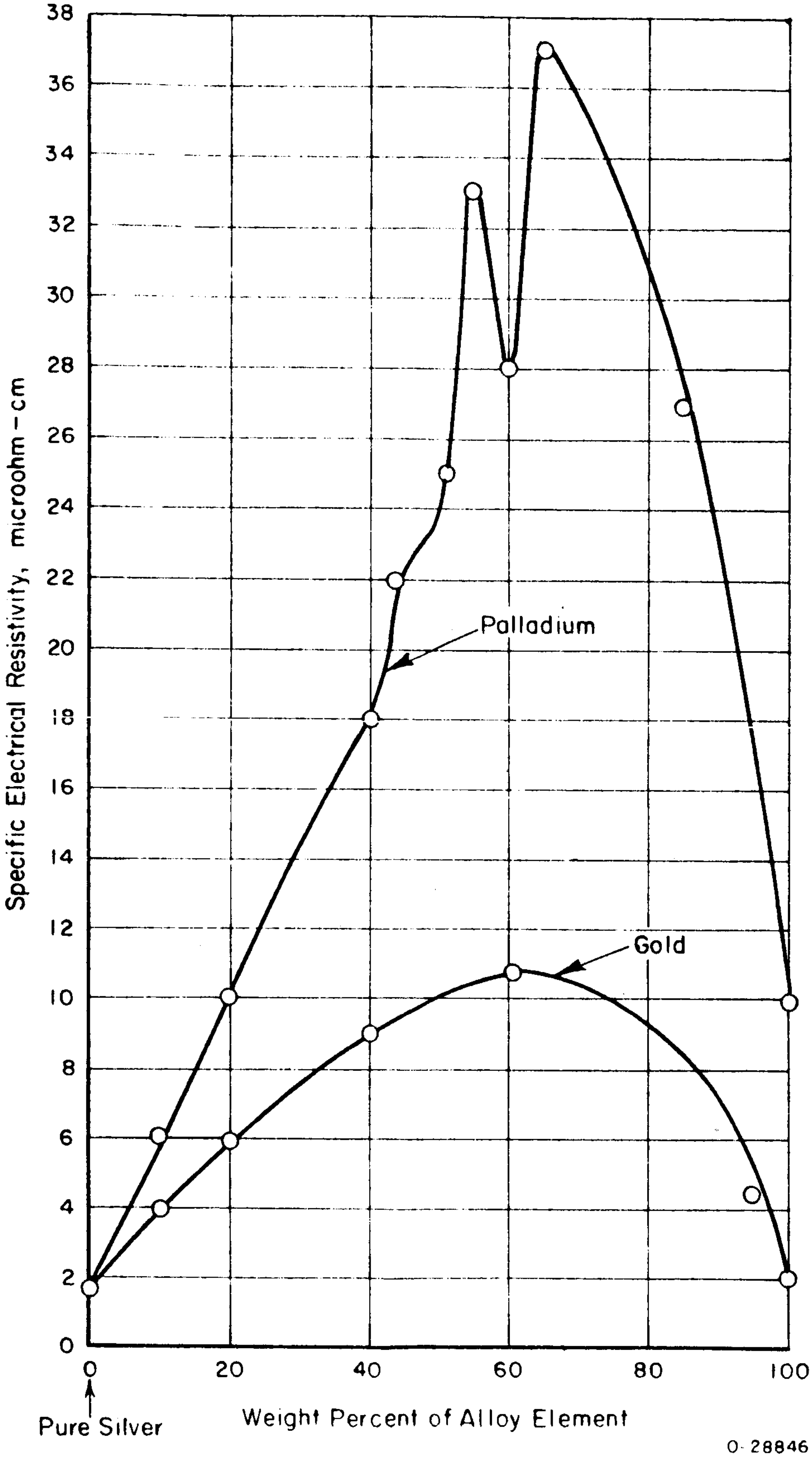


FIGURE B-1. EFFECT OF PALLADIUM OR GOLD ADDITIONS ON THE SPECIFIC ELECTRICAL RESISTIVITY OF ANNEALED SILVER ALLOYS

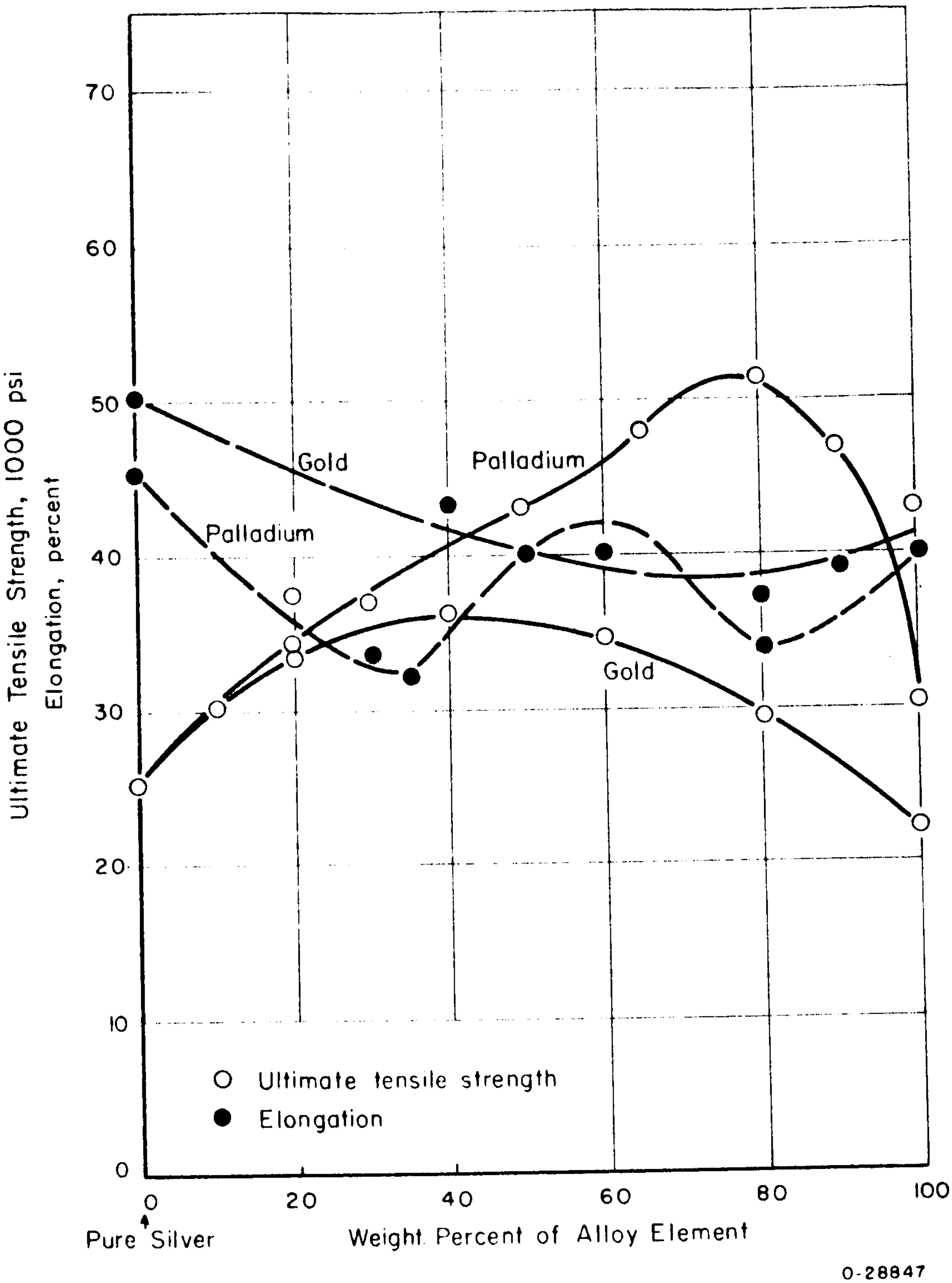


FIGURE B-2. EFFECT OF PALLADIUM OR GOLD ADDITIONS ON THE TENSILE PROPERTIES OF ANNEALED SILVER ALLOYS

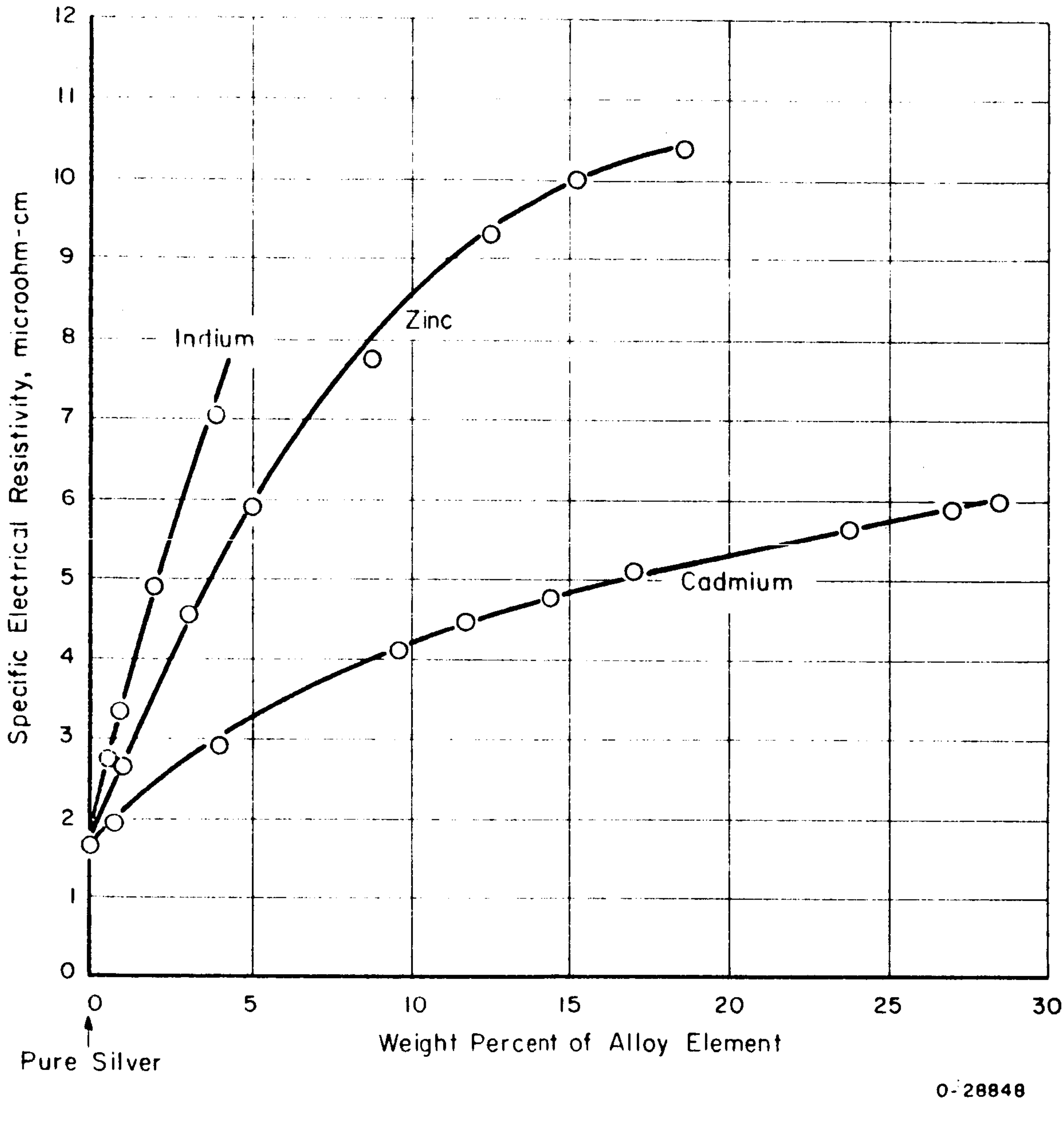


FIGURE B-3. EFFECT OF CADMIUM, ZINC, OR INDIUM ON THE SPECIFIC ELECTRICAL RESISTIVITY OF ANNEALED SILVER ALLOYS

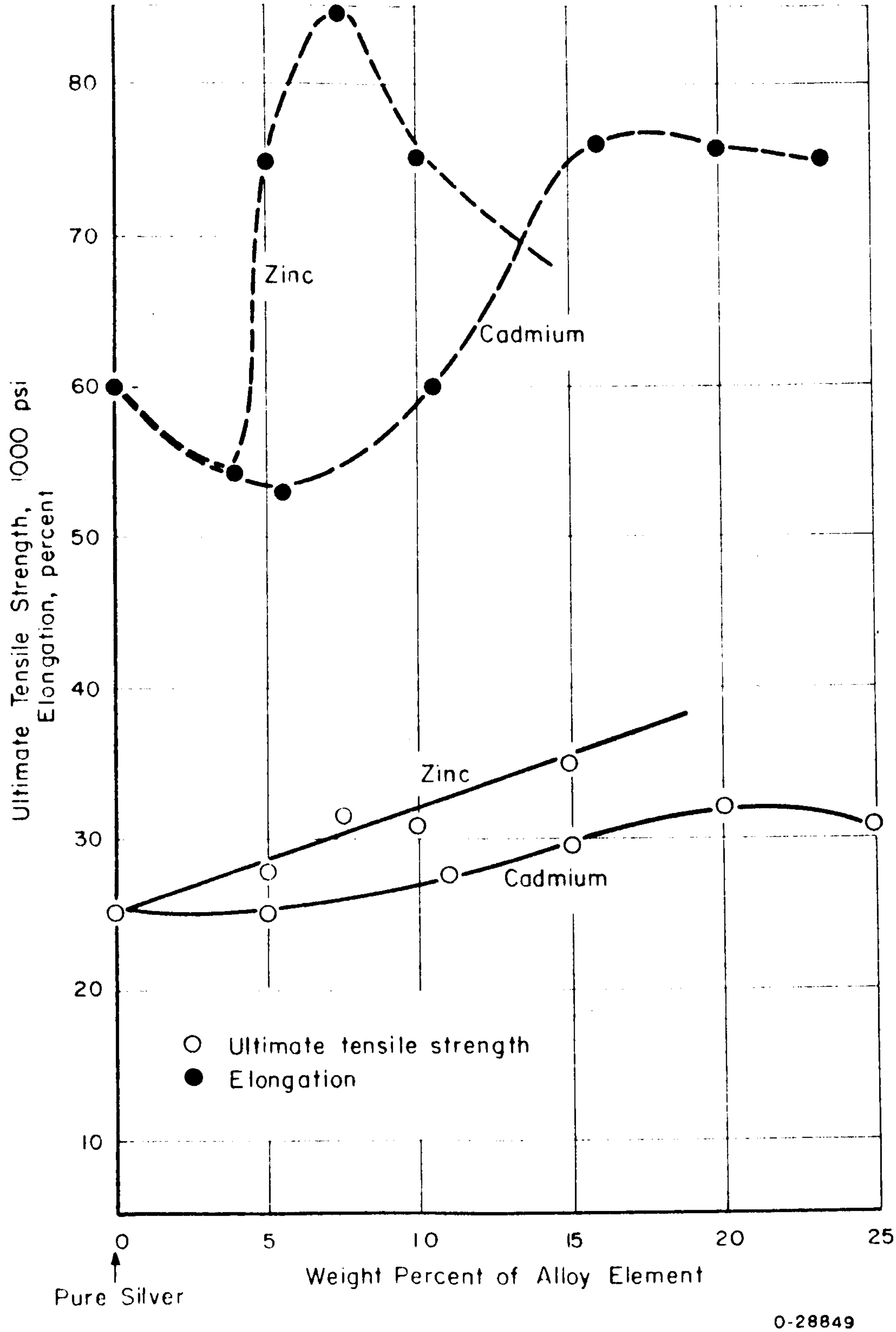


FIGURE B-4. EFFECT OF CADMIUM OR ZINC ADDITIONS ON THE TENSILE PROPERTIES OF ANNEALED SILVER ALLOYS

Coupled with the severe degradation of electrical conductivity, zinc and cadmium are also weak strengtheners of silver as shown in Figure B-4.[6, 7] However, silver-zinc and silver-cadmium alloys have good ductility Strength data for annealed silver-indium alloys could not be located.

Tin, Manganese, Magnesium, Antimony, Aluminum

Tin dissolves in solid silver to an extent of 10 percent. Manganese and magnesium both have solid solubilities in silver of about 7.5 percent (manganese is soluble to a much larger extent at high temperatures), while the solubility of antimony is slightly less. These alloy elements at the level of 6 to 10 percent addition have little or no tendency to precipitate from solid solution.

The room-temperature solid solubility of aluminum in silver is about 2 percent. However, about 6 percent aluminum dissolves in solid silver at 1100 F making silver-aluminum alloys susceptible to precipitation hardening.

The effects of tin, manganese, magnesium, antimony, and aluminum on the electrical resistivity of silver are shown in Figure B-5.[1, 3, 4, 5, 8, 9]

For dilute alloys, less than 2 percent alloy addition, the increase in the resistivity of silver is greatest for the moderately soluble elements in the order antimony, aluminum, manganese, tin, and magnesium.

As shown in Figure B-6, aluminum is a very effective strengthener of silver followed by antimony, tin, manganese, and magnesium.[1, 6, 7] With the exception of alloys containing more than 5 percent magnesium, the binary Ag-Sn, Mn, Sb, or Al alloys have good ductility.

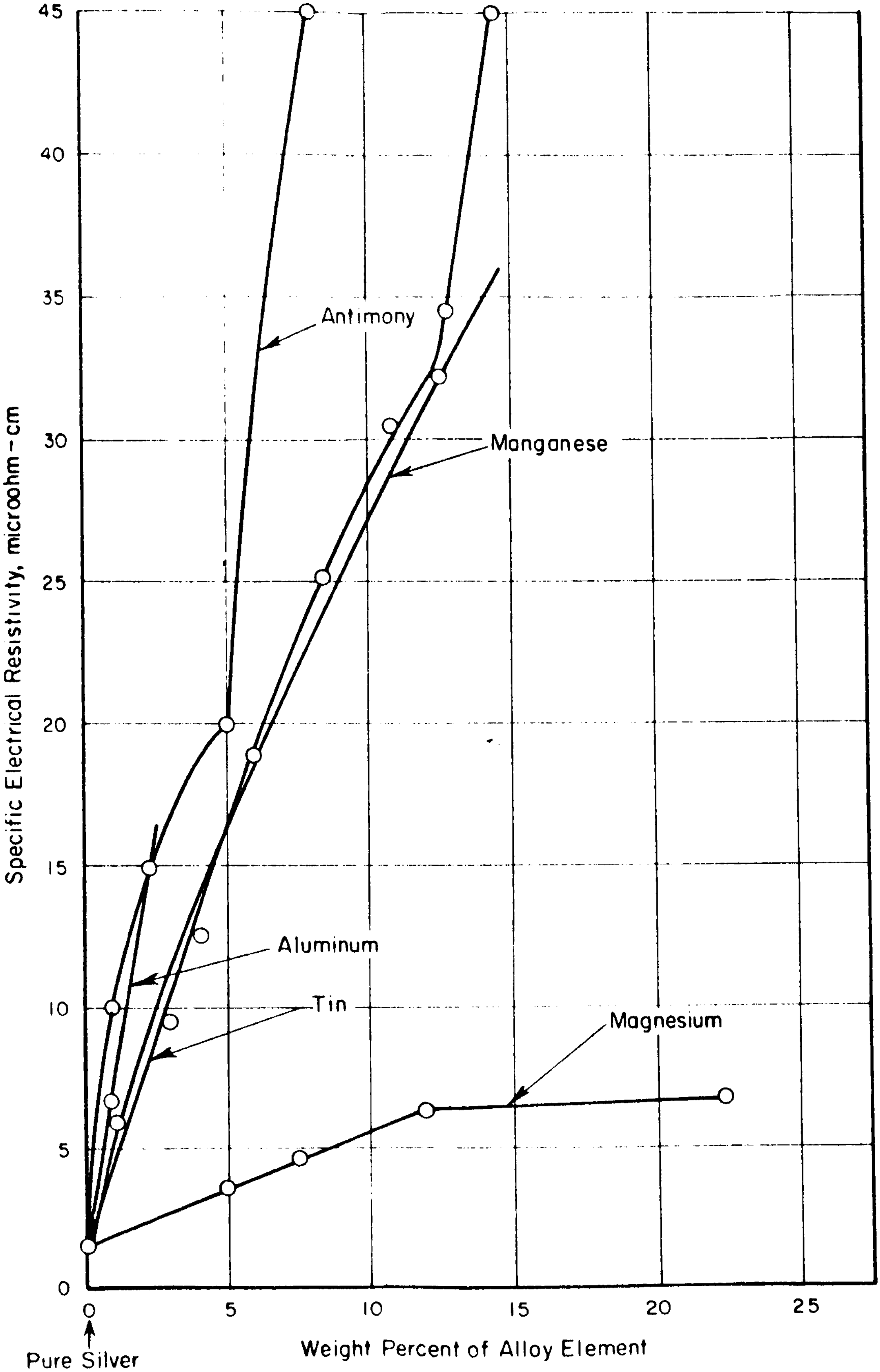
Other elements such as gallium, arsenic, and thallium which have solubilities in the range 2 to 20 percent in solid silver are not of interest for lead-wire alloys. These elements are insignificant strengtheners of silver, are low melting, and are highly volatile. Arsenic and thallium are also toxic.

Copper, Platinum, Germanium

Copper, platinum, and germanium all have appreciable solubility in solid silver at elevated temperatures but are soluble to an extent of less than 1 percent at near room temperature. Thus binary silver alloys with copper, platinum, or germanium should be age hardenable. However, in the case of copper, the kinetics of precipitation are very sluggish.

As shown in Figure B-7 copper additions have very little effect on the electrical resistivity of silver. Platinum increases the resistivity slightly, while germanium produces a larger increase.[1, 3, 4, 10]

Copper in solid solution is a very effective strengthener of silver as shown in Figure B-8.[10] High ductility of the silver-copper alloys suggests good fabricability. Data on the strengthening effects of platinum and germanium could not be found.



0-28850

FIGURE B-5. EFFECT OF TIN, MANGANESE, MAGNESIUM, ANTIMONY, OR ALUMINUM ON THE SPECIFIC ELECTRICAL RESISTIVITY OF ANNEALED SILVER ALLOYS

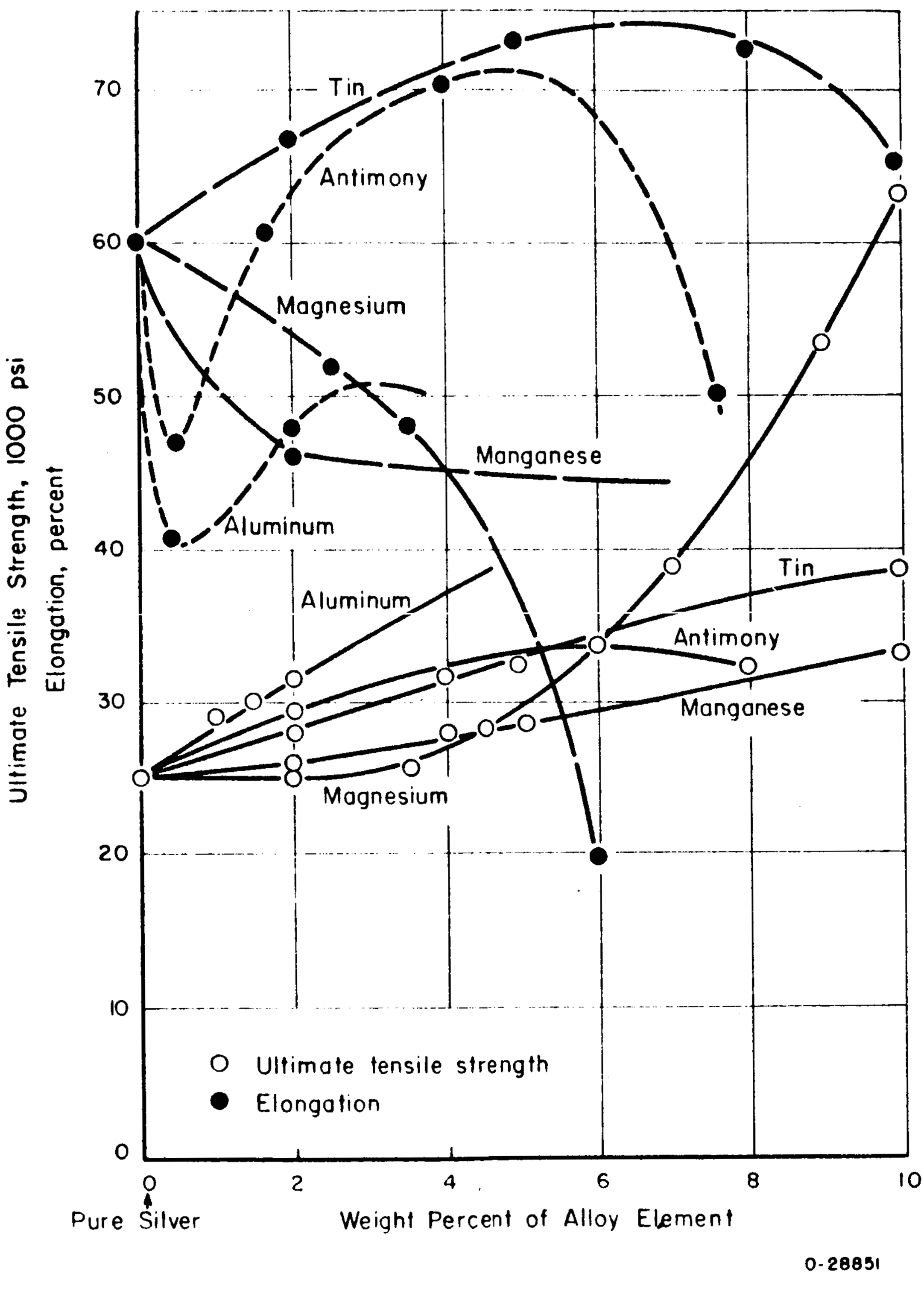


FIGURE B-6. EFFECT OF TIN, MANGANESE, MAGNESIUM, ANTIMONY, OR ALUMINUM ON THE TENSILE PROPERTIES OF ANNEALED SILVER ALLOYS

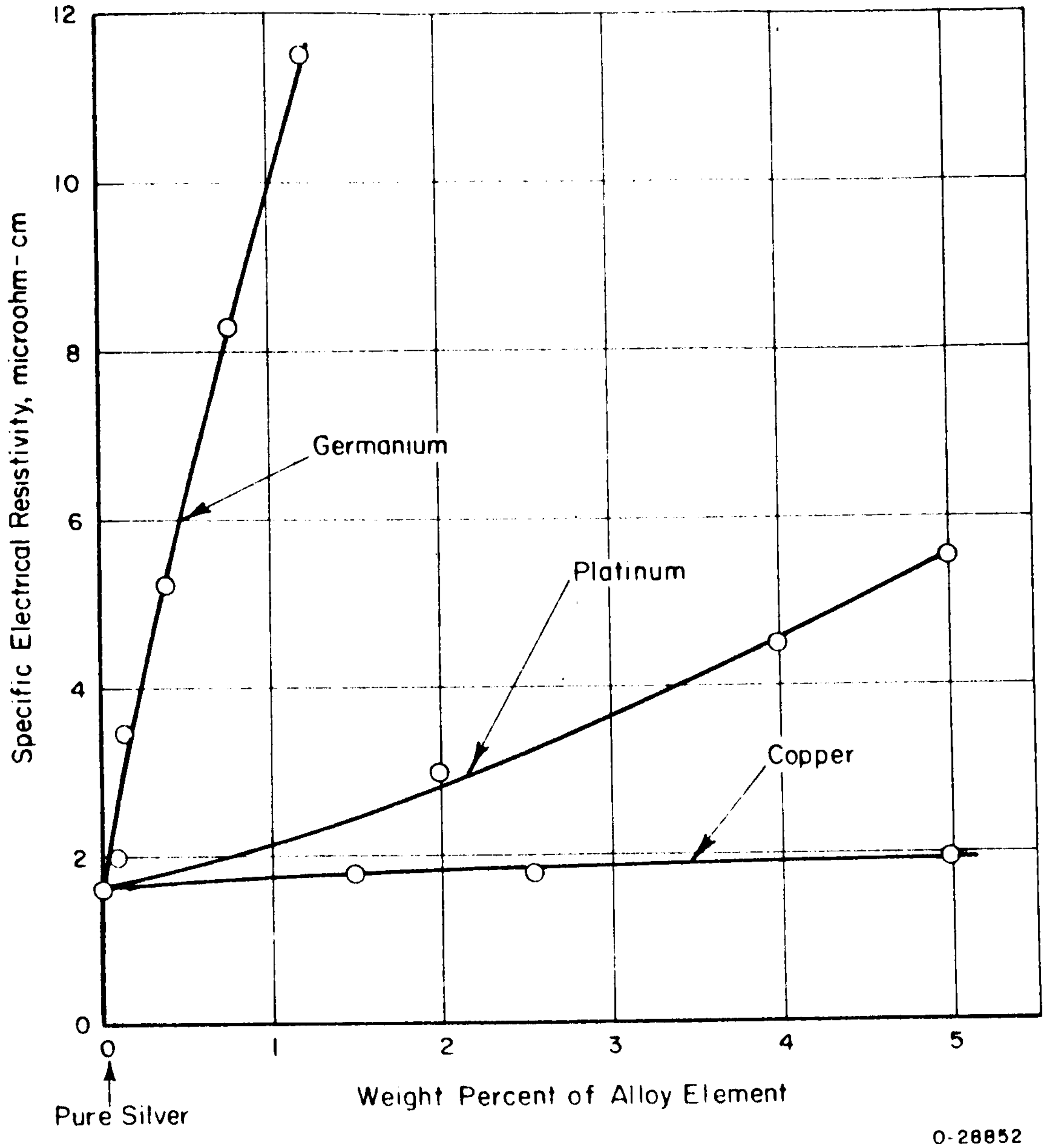


FIGURE B-7. EFFECT OF COPPER, PLATINUM, OR GERMANIUM ON THE SPECIFIC ELECTRICAL RESISTIVITY OF ANNEALED SILVER ALLOYS

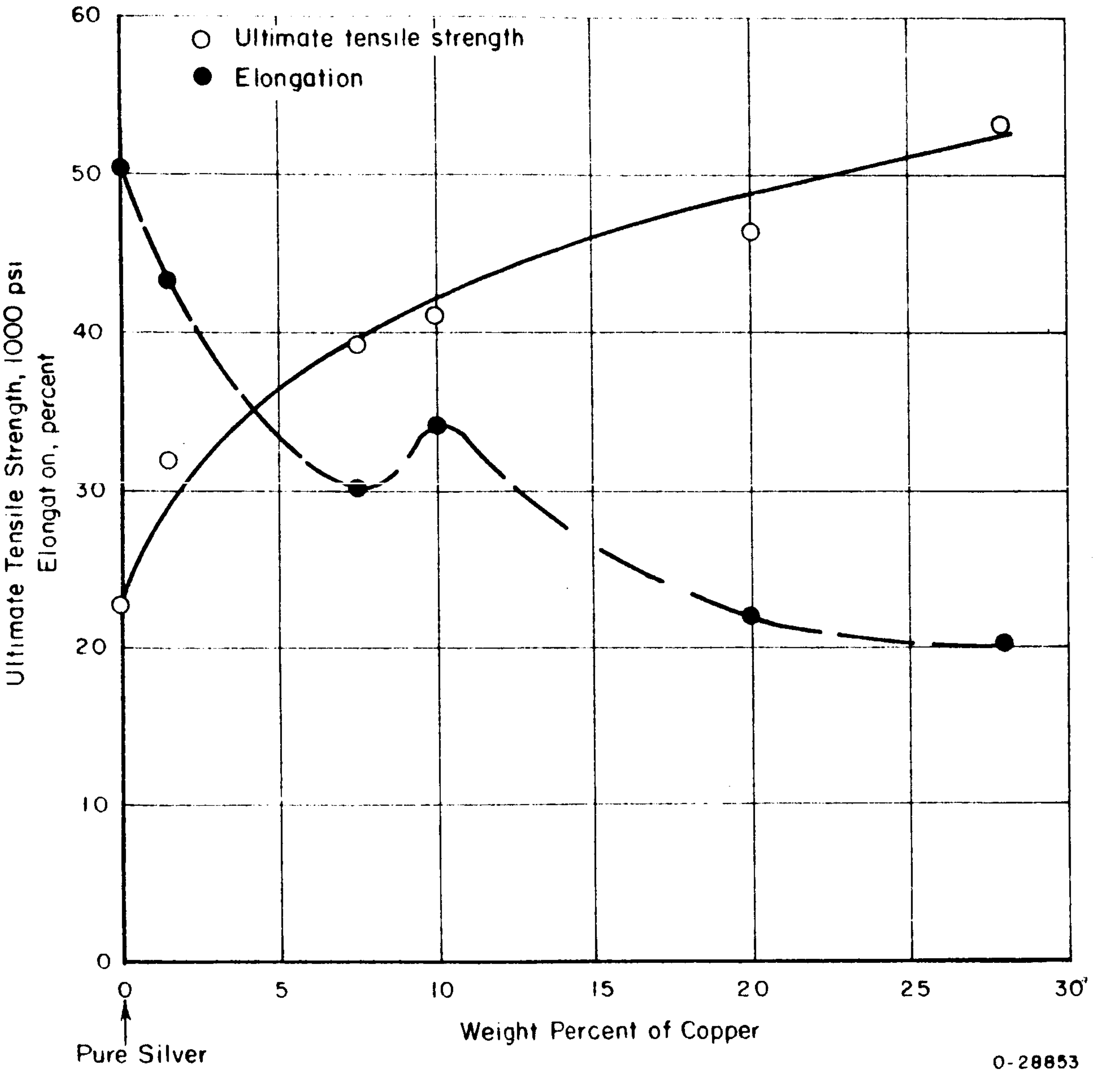


FIGURE B-8. TENSILE PROPERTIES OF ANNEALED SILVER-COPPER ALLOYS

Copper also significantly raises the recrystallization temperature of silver as shown below:[11]

Amount of Copper, weight percent	Temperature for Beginning of Recrystallization of Severely Cold Worked Alloy, F
Pure silver	300
0.01	390
0.3	450

Other effects of copper in silver have been pointed out in the discussion of the commercial Ag-1.5 Cu alloy in Appendix A.

Effects of Nil-Solubility Elements on Properties of Silver

The majority of metallic elements are either insoluble or are only slightly soluble in solid silver. Many of these elements are known to increase the recrystallization temperature and slightly increase the strength of silver while having little effect on the electrical resistivity.

Included among the elements that have little or no solid solubility in silver are nickel, silicon, ruthenium, rhodium, chromium, iron, titanium, beryllium and zirconium.

The only data that could be found to show the effects of nil-solubility elements on the electrical resistivity and strength of silver are shown in Figures B-9 and B-10.[1, 11]

The data in these figures clearly show the differences produced on the resistivity and strength of silver by elements that are in solid solution and insoluble elements that exist as a dispersed phase in the silver matrix. For example, silicon dissolves in silver to an extent of about 0.3 percent, while nickel dissolves to an extent of 0.1 percent. As shown in Figures B-9 and B-10 silicon and nickel appreciably alter the resistivity and strength of silver when present in solid solution. When silicon and nickel are added in amounts exceeding their solubility in solid silver, the excess becomes a dispersed phase in silver and does not further alter the resistivity, while slight strengthening continues.

Ruthenium and rhodium are insoluble in silver and have practically no effect, in amounts to 5 percent, on the resistivity. Although the data in Figure B-9 indicate that ruthenium slightly decreases the resistivity of silver, this result is questionable. Theoretically, the addition of insoluble elements, all of which have an electrical resistivity greater than silver, should increase the resistivity in linear proportion to the volume percent of the insoluble addition. As shown in Figure B-10 ruthenium does not increase the strength of silver.

The outstanding effect of some nil-solubility additions in raising the recrystallization and softening temperatures and in slowing grain growth in silver is illustrated by data in Table B-2.[12] Particularly noteworthy is the increase in hardness of silver alloyed with only 0.3 percent titanium or beryllium as well as the effects of 0.3 percent chromium and iron in inhibiting recrystallization.

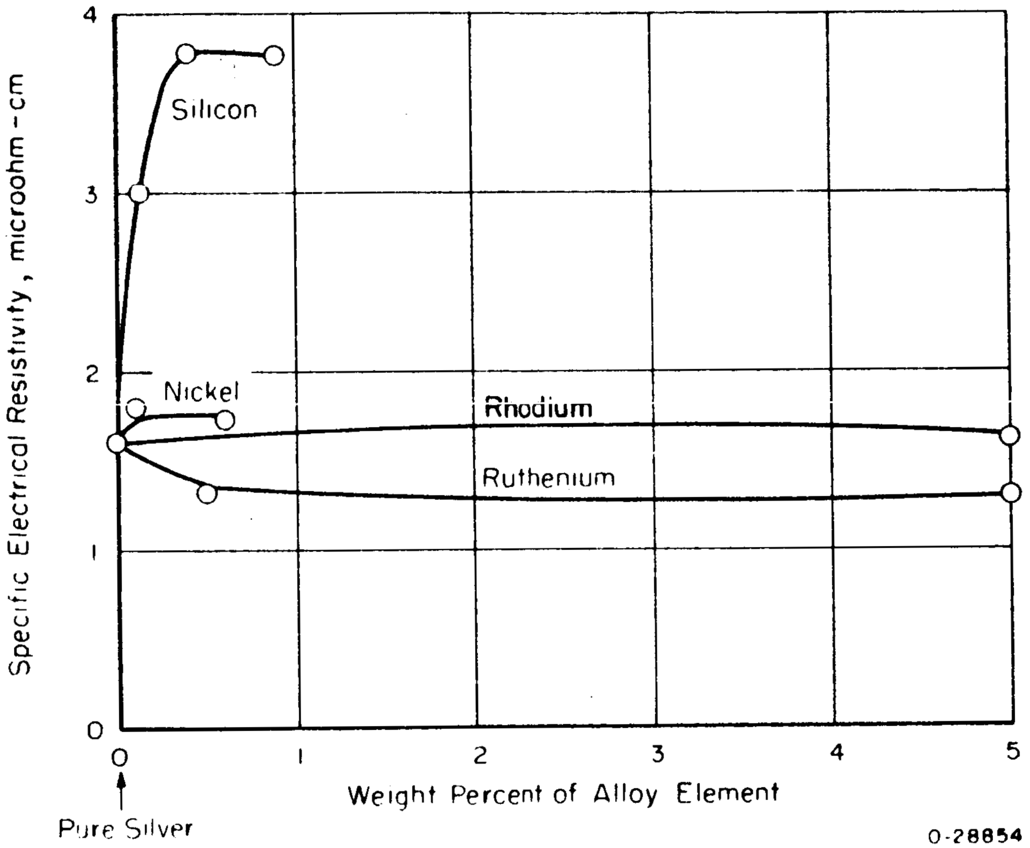


FIGURE B-9. EFFECT OF SILICON, NICKEL, RHODIUM, OR RUTHENIUM ON THE SPECIFIC ELECTRICAL RESISTIVITY OF ANNEALED SILVER ALLOYS

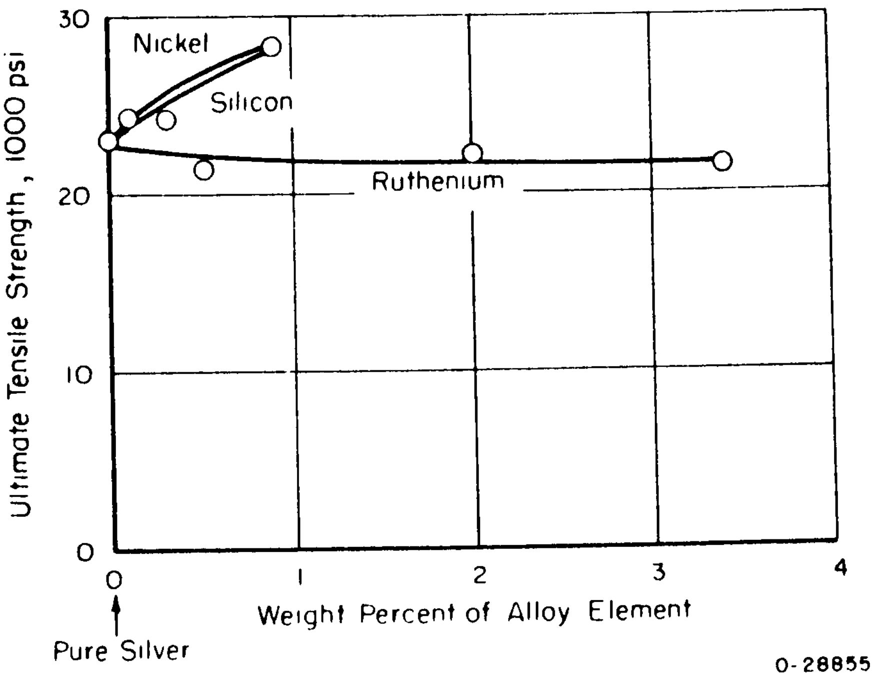


FIGURE B-10. EFFECT OF NICKEL, SILICON, OR RUTHENIUM ON THE TENSILE STRENGTH OF ANNEALED SILVER ALLOYS

TABLE B-2. EFFECTS OF SOME NIL-SOLUBILITY ADDITIONS ON THE SOFTENING, RECRYSTALLIZATION, AND GRAIN GROWTH OF SILVER(12)

Alloy Composition, weight percent	Temperature of 30-Minute Annealing Treatment, F							
	900		1100		1300		1500	
	Vickers Hardness	ASTM Grain Size No.(a)	Vickers Hardness	ASTM Grain Size No.(a)	Vickers Hardness	ASTM Grain Size No.(a)	Vickers Hardness	ASTM Grain Size No.(a)
Pure silver	42	1	41	>>1	38	--	35	--
Ag-0.3 Ti	68	--	--	--	--	<<8	44	1-1/2
Ag-0.3 Be	46	<8	--	8	46	7-1/2	50	6-1/2
Ag-0.3 Cr	45	Not recrystallized	--	Not recrystallized	41	7-1/2	40	--
Ag-0.3 Fe	43	Not recrystallized	--	Not recrystallized	41	7-1/2	40	--

(a) Mean number of grains per inch at 100X = 2^{n-1} where n = ASTM grain size number.

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(12) Unpublished data of W. H. Abbott of Battelle Memorial Institute.

APPENDIX C

TABULATION OF DATA ON LABORATORY-PROCESSED SILVER ALLOYS

TABLE C-1. HARDNESSES OF SILVER ALLOYS IN THE 90 PERCENT WORKED AND VARIOUS ANNEALED CONDITIONS

Alloy	Composition, weight percent	Hardness in 90 Percent Worked Condition[a], VHN	Hardness of Specimens Annealed for 1 Hour at the Indicated Temperatures, VHN[a]					
			400 F	600 F	800 F	1000 F	1200 F	1400 F
0	Ag	89	43	37	32	25	28	30
1	Ag-1 Cu	110	113	64	46	34	30	32
2	Ag-1.5 Cu	117	123	78	57	37	31	33
3	Ag-3 Cu	127	135	97	77	55	38	40
4	Ag-5 Cu	133	145	97	84	66	72	61
5	Ag-0.5 Pd	89	49	44	39	31	27	29
6	Ag-1 Pd	91	73	46	41	32	28	29
7	Ag-1 Au	91	43	38	38	32	27	28
8	Ag-1.5 Au	92	43	35	32	29	28	25
9	Ag-0.6 Pt	92	57	38	39	31	27	25
10	Ag-1.5 Pt	93	91	45	45	37	29	26
11	Ag-0.1 Ni	97	87	44	50	45	33	37
12	Ag-0.2 Ni	96	82	44	53	49	39	41
13	Ag-0.5 Ni	104	93	51	53	53	44	48
14	Ag-0.1 Cr	93	48	33	43	41	30	39
15	Ag-0.2 Cr	95	53	32	46	43	36	42
16	Ag-0.5 Cr	100	50	48	43	43	40	31
17	Ag-0.05 Ti	103	54	43	41	43	38	25
18	Ag-0.1 Ti	102	47	43	40	41	34	26
19	Ag-0.3 Ti	102	86	50	45	50	42	29
20	Ag-0.05 Zr	102	50	43	39	37	33	27
21	Ag-0.1 Zr	105	102	67	36	37	34	26
22	Ag-0.1 Be	100	61	49	41	44	41	35
23	Ag-1 Cu-0.2 Be	119	123	79	51	54	51	44
24	Ag-1 Ru	100	46	35	28	28	25	25
25	Ag-2 Ru	103	43	39	28	27	29	26
26	Ag-1 Cu-0.1 Ni	117	117	93	59	50	36	42
27	Ag-1 Cu-0.2 Ni	117	121	97	64	51	37	43
28	Ag-1.5 Cu-0.1 Ni	123	123	99	66	50	37	38
29	Ag-1.5 Cu-0.2 Ni	123	125	100	70	53	43	39
30	Ag-1 Cu-0.1 Al	113	119	79	70	33	32	31

(a) Vickers Hardness number using 1000-gram load. Values given are averages of four hardness measurements.

TABLE C-2. TENSILE AND ELECTRICAL PROPERTIES OF THE EXPERIMENTAL ALLOYS IN THE FULLY ANNEALED CONDITION[a]

			Tensile Properties at 75 F[c]				Electrical Properties at 75 F	
Alloy	Composition, weight percent	1-Hour Annealing Temperature[b], F	Ultimate Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation, percent in 10 inches	Reduction in Area, percent	Specific Resistivity, microohm-cm	Average Electrical Conductivity, percent IACS
0	Ag	800	25-25 (25)	7-8 (8)	45-48 (47)	95-95 (95)	1.65-1.65-1.64 (1.65)	104.7
1	Ag-1 Cu	1000	30-30 (30)	8-8 (8)	44-43 (44)	97-97 (97)	1.72-1.73-1.73 (1.73)	98.7
2	Ag-1.5 Cu	1000	31-31 (31)	9-10 (10)	47-47 (47)	97-97 (97)	1.80-1.78-1.78 (1.79)	96.6
3	Ag-3 Cu	1200	34-34 (34)	10-10 (10)	40-38 (39)	85-85 (85)	1.83-1.87-1.91 (1.87)	92.2
4	Ag-5 Cu	1400	42-42 (42)	20-21 (21)	31-31 (31)	44-44 (44)	1.91-1.94-1.94 (1.93)	89.3
5	Ag-0.5 Pd	1200	26-26 (26)	7-7 (7)	38-44 (41)	93-93 (93)	1.88-1.88-1.89 (1.88)	91.6
6	Ag-1 Pd	1200	26-26 (26)	6-5 (6)	41-42 (42)	94-94 (94)	2.05-2.03-2.01 (2.03)	85.0
7	Ag-1 Au	800	26-26 (26)	8-8 (8)	51-50 (50)	95-95 (95)	1.83-1.83-1.82 (1.83)	94.3
8	Ag-1.5 Au	800	26-26 (26)	10-10 (10)	46-45 (46)	95-95 (95)	1.87-1.91-1.91 (1.90)	90.9
9	Ag-0.6 Pt	1200	27-27 (27)	7-7 (7)	34-37 (36)	85-85 (85)	2.10-2.08-2.12 (2.10)	82.1
10	Ag-1.5 Pt	1200	27-27 (27)	7-7 (7)	42-43 (43)	94-94 (94)	2.70-2.69-2.67 (2.69)	64.2
11	Ag-0.1 Ni	1400	26-26 (26)	8-7 (8)	39-41 (40)	94-94 (94)	1.65-1.68-1.67 (1.67)	103.5
12	Ag-0.2 Ni	1400	27-27 (27)	9-10 (10)	44-45 (45)	95-95 (95)	1.73-1.73-1.73 (1.73)	99.7
13	Ag-0.5 Ni	1400	28-28 (28)	9-9 (9)	41-37 (39)	95-95 (95)	1.58-1.59-1.62 (1.60)	108.0
14	Ag-0.1 Cr	1400	27-27 (27)	7-8 (8)	36-39 (38)	87-87 (87)	1.74-1.75-1.76 (1.75)	98.5
15	Ag-0.2 Cr	1400	27-27 (27)	8-9 (9)	39-43 (41)	95-95 (95)	1.63-1.63-1.63 (1.62)	106.4
16	Ag-0.5 Cr	1400	27-27 (27)	8-9 (9)	35-31 (33)	90-90 (90)	1.60-1.60-1.59 (1.60)	108
17	Ag-0.05 Ti	1200	27-27 (27)	10-11 (11)	45-44 (45)	96-96 (96)	2.04-2.05 (2.05)	83.9
18	Ag-0.1 Ti	1200	26-26 (26)	9-8 (9)	46-45 (46)	96-96 (96)	2.14-2.14-2.14 (2.13)	80.9
19	Ag-0.3 Ti	1200	27-27 (27)	12-11 (12)	41-41 (41)	95-95 (95)	2.17-2.20-2.16 (2.18)	79.2
20	Ag-0.05 Zr	1200	26-26 (26)	7-7 (7)	45-44 (45)	96-96 (96)	1.92-1.96-1.92 (1.93)	89.2
21	Ag-0.1 Zr	1200	26-26 (26)	8-8 (8)	41-42 (42)	96-96 (96)	2.46-2.39-2.40 (2.42)	71.4
22	Ag-0.1 Be	1200	27-27 (27)	10-10 (10)	46-46 (46)	95-95 (95)	1.67-1.68-1.69 (1.68)	102.7
23	Ag-1 Cu-0.2 Be	1400	30-30 (30)	10-10 (10)	32-31 (32)	94-94 (94)	1.76-1.74-1.74 (1.75)	98.3
24	Ag-1 Ru[d]	--	--	--	--	--	--	--
25	Ag-2 Ru	1400	26-26 (26)	7-8 (8)	28-28 (28)	45-45 (45)	1.58-1.58-1.56 (1.57)	109.6
26	Ag-1 Cu-0.1 Ni	1200	31-31 (31)	12-11 (12)	40-40 (40)	95-95 (95)	1.79-1.78-1.76 (1.78)	97.1
27	Ag-1 Cu-0.2 Ni	1200	31-31 (31)	12-12 (12)	39-40 (40)	94-94 (94)	1.78-1.78-1.77 (1.78)	97.1
28	Ag-1.5 Cu-0.1 Ni	1200	32-32 (32)	12-12 (12)	38-39 (39)	95-95 (95)	1.84-1.85-1.83 (1.84)	93.5
29	Ag-1.5 Cu-0.2 Ni	1400	31-31 (31)	9-10 (10)	38-36 (37)	94-94 (94)	1.91-1.92-1.93 (1.92)	89.8
30	Ag-1 Cu-0.1 Al[e]	--	--	--	--	--	2.73-2.75-2.78 (2.75)	62.8

(a) Properties were measured on 0.050-inch-diameter wires.
(b) All samples were air cooled from the annealing treatments.
(c) Average values are given in parentheses.
(d) Alloy 24 contained less than 0.05 percent Ru and was not evaluated.
(e) Tensile properties of Alloy 30 were not determined because its very low electrical conductivity eliminated it from consideration.

TABLE C-3. TENSILE AND ELECTRICAL PROPERTIES OF THE EXPERIMENTAL ALLOYS IN THE WROUGHT CONDITION[a]

			Tensile Properties at 75 F[b]				Electrical Properties	
Alloy	Composition, weight percent	Amount of Work at 75 F, percent reduction in area	Ultimate Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation, percent	Reduction in Area, percent	Specific Resistivity, microohm-cm	Average Electrical Conductivity, percent IACS
0	Ag	15	30-30 (30)	26-26 (26)	34-37 (36)[d]	93-93 (93)		
		30	37-37 (37)	36-34 (35)	3-3 (3)[c]	94-94 (94)	1.68-1.68-1.69 (1.68)	102.4
		63	46-46 (46)	44-41 (43)	3-3 (3)[c]	95-93 (94)	1.71-1.70-1.67 (1.69)	101.8
		90	49-49 (49)	44-46 (45)	3-4 (4)[c]	95-95 (95)	1.71-1.73-1.69 (1.71)	100.3
1	Ag-1 Cu	30	40	40	2[c]	91	1.72-1.74-1.74 (1.73)	99.5
		63	52-53 (53)	51-50 (51)	2-3 (3)[c]	93-93 (93)	1.83-1.84-1.85 (1.84)	93.6
		90	63-63 (63)	56-56 (56)	2-3 (3)[c]	88-88 (88)	1.86-1.86-1.86 (1.86)	92.3
2	Ag-1.5 Cu	30	44-44 (44)	42-42 (42)	3-3 (3)[c]	96-96 (96)	1.83-1.83-1.83 (1.83)	94.1
		63	56-56 (56)	49-50 (50)	3-3 (3)[c]	94-94 (94)	1.91-1.92-1.85 (1.89)	91.1
		90	68-68 (68)	59-61 (60)	4-2 (3)[c]	90-90 (90)	1.95-1.91-1.98-1.83 (1.92)	89.9
3	Ag-3 Cu	8	35-36 (36)	30-29 (30)	29-30 (30)[c]	87-87 (87)	1.98-1.98-1.98 (1.98)	87.1
		30	50-50 (50)	49-47 (48)	3-3 (3)[c]	66-66 (66)	1.99-1.96-1.97 (1.97)	87.4
		90	79-77 (78)	73-71 (72)	3-2 (3)[c]	89-89 (89)	2.01-2.09-2.11 (2.10)	82.1
4	Ag-5 Cu	30	56-56 (56)	54-54 (54)	2-2 (2)[c]	73-73 (73)	1.98-1.98-1.96 (1.97)	87.4
		63	67-67 (67)	64-63 (64)	3-4 (4)[c]	74-74 (74)		
		90	77-79 (78)	77-74 (76)	3-3 (3)[c]	74-74 (74)	2.10-2.13-2.12 (2.12)	81.5
5	Ag-0.5 Pd	30	38-37 (38)	37-36 (37)	4-2 (3)[c]	93-93 (93)	1.93-1.93-1.93 (1.93)	89.3
		63	46-46 (46)	44-43 (44)	3-2 (3)[c]	93-93 (93)	1.87-1.90-1.91 (1.89)	91.9
		90	52-52 (52)	41-44 (43)	3-3 (3)[d]	93-93 (93)	1.99-1.96-1.96 (1.97)	87.4
6	Ag-1 Pd	30	40-40 (40)	37-38 (38)	3-5 (4)[c]	93-93 (93)	2.12-2.13-2.13 (2.13)	81.1
		63	48-48 (48)	45-45 (45)	4-3 (4)[c]	92-92 (92)	2.17-2.18-2.18 (2.18)	79.2
		90	50-52 (51)	48-48 (48)	2-3 (3)[c]	92-92 (92)	2.19-2.19-2.14 (2.17)	79.4
7	Ag-1 Au	30	37-37 (37)	36-36 (36)	4-4 (4)[c]	94-94 (94)	1.85-1.87-1.87 (1.86)	92.5
		63	44-45 (45)	38-42 (40)	4-4 (4)[d]	93-93 (93)	1.89-1.89-1.91 (1.90)	90.9
		90	50-50 (50)	43-46 (45)	3-3 (3)[d]	93-93 (93)	1.89-1.90-1.88 (1.89)	91.1
8	Ag-1.5 Au	30	37-37 (37)	35-35 (35)	3-3 (3)[c]	94-94 (94)	1.94-1.95-1.97 (1.95)	88.3
		63	44-44 (44)	41-42 (42)	2-2 (2)[c]	93-93 (93)	1.98-1.98-1.97 (1.98)	87.3
		90	50-50 (50)	46-45 (46)	2-3 (3)[d]	94-94 (94)	1.99-2.02-1.98 (1.99)	86.3

TABLE C-3. (Continued)

Alloy	Composition, weight percent	Amount of Work at 75 F, percent reduction in area	Tensile Properties at 75 F: Ultimate Strength, ksi	Tensile Properties at 75 F: 0.2 Percent Offset Yield Strength, ksi	Tensile Properties at 75 F: Elongation, percent	Tensile Properties at 75 F: Reduction in Area, percent	Electrical Properties: Specific Resistivity, microohm-cm	Electrical Properties: Average Electrical Conductivity, percent IACS
9	Ag-0.6 Pt	30	41-41 (41)	40-40 (40)	3-3 (3)(d)	92-92 (92)	2.10-2.11-2.14 (2.12)	81.4
		63	46-46 (46)	43-41 (42)	2-2 (2)(d)	92-92 (92)	2.15-2.15-2.14 (2.15)	80.2
		90	53-53 (53)	45-49 (47)	3-3 (3)(d)	94-94 (94)	2.12-2.12-2.14 (2.13)	80.5
10	Ag-1.5 Pt	30	41-41 (41)	40-40 (40)	3-4 (4)(c)	93-93 (93)	2.72-2.72-2.70 (2.71)	63.6
		63	50-49 (50)	47-46 (47)	3-3 (3)(c)	91-91 (91)	2.76-2.78-2.77 (2.77)	62.2
		90	54-52 (53)	42-48 (45)	2-3 (3)(c)	92-92 (92)	2.74-2.75-2.75 (2.75)	62.8
11	Ag-0.1 Ni	30	42-42 (42)	38-38 (38)	3-2 (3)(c)	95-95 (95)	1.76-1.76-1.81 (1.78)	97.0
		63	49-49 (49)	49-41 (45)	3-3 (3)(c)	91-91 (91)	1.72-1.72-1.71 (1.72)	100.4
		90	56-56 (56)	50-53 (52)	2-3 (3)(c)	91-91 (91)	1.75-1.78-1.78-1.78 (1.77)	97.3
12	Ag-0.2 Ni	30	42-42 (42)	41-41 (41)	2-3 (3)(c)	93-93 (93)	1.68-1.68-1.69 (1.68)	102.4
		63	48-48 (48)	45-44 (45)	5-4 (5)(d)	89-89 (89)	1.70-1.72-1.71 (1.71)	100.9
		90	55-55 (55)	51-50 (51)	4-3 (4)(c)	86-86 (86)	1.76-1.77-1.77 (1.77)	97.6
13	Ag-0.5 Ni	15	34-34 (34)	30-30 (30)	24-22 (23)(c)	95-95 (95)	1.71-1.73-1.75 (1.73)	99.7
		30	41-41 (41)	36-39 (38)	3-3 (3)(c)	93-93 (93)	1.74-1.76-1.78 (1.76)	98.0
14	Ag-0.1 Cr	30	39-39 (39)	36-36 (36)	4-4 (4)(c)	94-94 (94)	1.67-1.67-1.68 (1.67)	103.1
		63	46-46 (46)	42-43 (43)	4-3 (4)(d)	92-92 (92)	1.68-1.68-1.68 (1.68)	102.6
		90	51-51 (51)	47-47 (47)	4-4 (4)(d)	93-93 (93)	1.73-1.73-1.71 (1.72)	100.3
15	Ag-0.2 Cr	8	29-29 (29)	26-24 (25)	46-44 (45)(c)	92-92 (92)	1.71-1.71-1.71 (1.71)	100.9
		30	40-40 (40)	39-39 (39)	4-4 (4)(d)	93-93 (93)	1.69-1.68-1.66 (1.68)	102.9
		90	51-51 (51)	48-48 (48)	2-3 (3)(c)	88-88 (88)	1.73-1.73-1.74-1.71 (1.73)	99.7
16	Ag-0.5 Cr	15	31-31 (31)	27-27 (27)	27-12 (18)(c)	93-93 (93)	1.71-1.71-1.73 (1.72)	100.5
		30	39-37 (38)	37-37 (37)	2-1 (2)(c)	58-86 (77)	1.72-1.75-1.78 (1.75)	98.5
17	Ag-0.05 Ti	15	30-30 (30)	26-27 (27)	29-27 (28)(d)	95-95 (95)	2.26-2.28-2.26 (2.27)	76.0
		30	37-35 (36)	36-32 (34)	7-7 (7)(d)	83-89 (86)	2.35-2.36-2.31 (2.34)	73.7
18	Ag-0.1 Ti	15	30-30 (30)	26-26 (26)	29-25 (27)(c)	96-96 (96)	2.27-2.29-2.30 (2.29)	75.4
		30	37-37 (37)	35-35 (35)	2-2 (2)(c)	95-85 (90)	2.30-2.31-2.31 (2.31)	74.8
19	Ag-0.3 Ti	15	31-31 (31)	28-27 (28)	22-25 (24)(c)	95-95 (95)	2.31-2.30-2.31 (2.31)	74.5
		30	38-38 (38)	36-37 (37)	3-2 (3)(c)	93-93 (93)	2.29-2.30-2.33 (2.31)	74.8

TABLE C-3. (Continued)

Alloy	Composition, weight percent	Amount of Work at 75 F, percent reduction in area	Tensile Properties at 75 F: Ultimate Tensile Strength, ksi	Tensile Properties at 75 F: 0.2 Percent Offset Yield Strength, ksi	Tensile Properties at 75 F: Elongation, percent	Tensile Properties at 75 F: Reduction in Area, percent	Electrical Properties: Specific Resistivity, microohm-cm	Electrical Properties: Average Electrical Conductivity, percent IACS
20	Ag-0.05 Zr	15	29-29 (29)	26-26 (26)	26-25 (26)(c)	95-95 (95)	2.01-2.02-2.05 (2.03)	84.9
		30	37-37 (37)	36-36 (36)	2-3 (3)(c)	94-85 (90)	2.11-2.11-2.12 (2.11)	81.6
21	Ag-0.1 Zr	15	30-30 (30)	27-27 (27)	22-24 (23)(c)	85-85 (85)	2.54-2.57-2.58 (2.56)	67.1
		30	38-39 (39)	36-37 (37)	2-3 (3)(c)	94-85 (90)	2.58-2.59-2.60 (2.59)	66.6
22	Ag-0.1 Be	15	32-32 (32)	28-29 (29)	23-23 (23)(c)	92-92 (92)	1.64-1.66-1.66 (1.65)	104.0
		30	39-39 (39)	38-38 (38)	3-3 (3)(c)	88-88 (88)	1.65-1.68-1.69 (1.67)	103.1
23	Ag-1 Cu-0.2 Be	15	36-36 (36)	33-33 (33)	17-18 (18)(c)	95-95 (95)	1.75-1.75-1.73 (1.74)	98.8
		30	44-45 (45)	41-41 (41)	3-2 (3)(c)	91-91 (91)	1.77-1.78-1.78 (1.78)	97.1
24	Ag-1 Ru	15	30-30 (30)	26-27 (27)	8-15 (12)(c)	84-84 (84)	1.62-1.63-1.64 (1.63)	105.7
		30	38	37	3(c)	89	1.67-1.69-1.70 (1.69)	102.3
25	Ag-2 Ru	15	30-30 (30)	27-28 (28)	11-13 (12)(c)	63-63 (63)	1.66-1.68-1.71 (1.68)	102.4
		30	39-39 (39)	37-37 (37)	2-2 (2)(c)	78-78 (78)	1.69-1.71-1.71 (1.70)	101.3
26	Ag-1 Cu-0.1 Ni	8	34-34 (34)	30-29 (30)	35-33 (34)(c)	96-96 (96)	1.80-1.81-1.84 (1.82)	94.9
		30	46-45 (46)	45-43 (44)	2-2 (2)(c)	88-88 (88)	1.82-1.82-1.81 (1.81)	94.8
		90	69-69 (69)	58-66 (62)	4-3 (4)(c)	84-84 (84)	1.88-1.88-1.86 (1.87)	91.5
27	Ag-1 Cu-0.2 Ni	30	47-47 (47)	42-41 (42)	3-3 (3)(c)	92-92 (92)	1.79-1.81-1.80 (1.80)	95.8
		63	56-56 (56)	52-53 (53)	4-4 (4)(d)	89-89 (89)	1.84-1.83-1.82 (1.83)	94.1
		90	70-70 (70)	65-63 (64)	5-5 (5)(d)	75-75 (75)	1.89-1.88-1.90 (1.89)	91.2
28	Ag-1.5 Cu-0.1 Ni	8	35-35 (35)	30-30 (30)	27-25 (26)(c)	94-94 (94)	1.85-1.86-1.87 (1.86)	92.6
		30	47-47 (47)	44-46 (45)	3-2 (3)(c)	90-90 (90)	1.87-1.87-1.86 (1.86)	92.4
		90	74-73 (74)	67-66 (67)	4-3 (4)(c)	86-86 (86)	1.93-1.95-1.91 (1.93)	89.3
29	Ag-1.5 Cu-0.2 Ni	8	36-36 (36)	31-31 (31)	26-23 (25)(c)	93-93 (93)	1.85-1.86-1.88 (1.86)	92.2
		30	48-48 (48)	47-46 (47)	3-3 (3)(c)	90-90 (90)	1.87-1.87-1.87 (1.87)	92.2
		90	75-75 (75)	67-67 (67)	3-3 (3)(c)	74-74 (74)	1.94-1.96-1.96 (1.95)	88.2
30	Ag-1 Cu-0.1 Al	30	44-44 (44)	43-43 (43)	3-3 (3)(c)	94-94 (94)	2.87-2.89-2.88 (2.88)	59.8
		63	56-56 (56)	53-49 (51)	2-3 (3)(c)	92-92 (92)	2.94-2.94-2.93 (2.94)	58.7
		90	69-68 (69)	61-62 (62)	4-3 (4)(c)	61-62 (62)	2.98-2.97-2.98 (2.98)	58.0

Footnotes appear on the following page.

Footnotes to Table C-3.

(a) Properties of specimens worked 15, 30, 63, or 90 percent reduction in area were measured on 0.050-inch-diameter wire. Properties of specimens worked 8 percent reduction in area were measured on 0.048-inch-diameter wire.
(b) Average values are given in parentheses.
(c) Gage length was 4 inches.
(d) Gage length was 2 inches.

TABLE C-4. TENSILE PROPERTIES OF SELECTED, COLD-WORKED ALLOYS AFTER EXPOSURE TO SIMULATED TEFLON-CURING CYCLE[(a)]

Alloy	Composition, weight percent	Amount of Work Before 700 F Exposure, percent reduction in area	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation, percent	Average Reduction in Area, percent
0	Ag	15	25.2, 25.3	7.1, 8.1	46.5, 48[(c)]	93.6
		30	24.6, 24.6	7.6, 7.9	51.5, 53[(c)]	94.6
2	Ag-1.5 Cu	30	39.4, 39.6	35.2, 35.2	12.5, 11.0[(b)]	94.8
5	Ag-0.5 Pd	30	25.3, 25.4	8.7, 8.6	60.0, 58.0[(c)]	95.2
11	Ag-0.1 Ni	30	27.4, 27.3	11.4, 11.6	43.5, 45.0[(b)]	94.8
14	Ag-0.1 Cr	63	26.6, 26.5	10.7, 11.0	56.5, 56.0[(c)]	96.2
22	Ag-0.1 Be	15	26.9, 26.9	8.4, 8.1	42.0, 41.0[(b)]	91.6
23	Ag-1 Cu-0.2 Be	15	34.4, 34.4	28.5, 28.9	21.2, 22.0[(b)]	93.4
26	Ag-1 Cu-0.1 Ni	8	32.8, 32.7	25.1, 24.6	35.5, 29.5[(c)]	94.8
27	Ag-1 Cu-0.2 Ni	30	40.7, 40.7	37.2, 37.6	14.0, 14.0[(c)]	89.1
28	Ag-1.5 Cu-0.1 Ni	8	34.3, 34.3	26.2, 26.2	30.0, 28.8[(b)]	94.4
29	Ag-1.5 Cu-0.2 Ni	8	35.2, 35.2	27.3, 27.6	25.4, 29.2[(b)]	93.1

(a) Wrought alloys were heated for 2 minutes at 700 F before evaluation.
(b) Gage lengths were 4 inches.
(c) Gage lengths were 2 inches.

TABLE C-5. TENSILE AND ELECTRICAL PROPERTIES OF SELECTED ALLOYS WITH COPPER IN THE PARTIALLY ANNEALED CONDITION[a]

Alloy	Composition, weight percent	1-Hour Annealing Temperature[b], F	Tensile Properties at 700 F: Ultimate Strength, ksi	Tensile Properties at 700 F: 0.2 Percent Offset Yield Strength, ksi	Tensile Properties at 700 F: Elongation, percent in 4 inches	Tensile Properties at 700 F: Reduction in Area, percent	Electrical Properties at 75 F: Specific Resistivity, microohm-cm	Electrical Properties at 75 F: Average Electrical Conductivity, percent IACS
2	Ag-1.5 Cu	800	33.6, 33.6	19.1, 19.1	40.8, 44.3	96.7, 96.7	1.83, 1.83, 1.82	94.3
23	Ag-1 Cu-0.2 Be	800	31.4, 31.9	17.3, 17.9	42.0, 42.0	94.2, 94.2	1.76, 1.78, 1.72	98.3
26	Ag-1 Cu-0.1 Ni	800	33.8	21.4	40.0	95.7	1.77, 1.76, 1.76	97.7
27	Ag-1 Cu-0.2 Ni	800	34.2	21.4	37.5	93.6	1.79, 1.77, 1.76	97.2
28	Ag-1.5 Cu-0.1 Ni	800	35.6, 35.5	24.4, 24.3	33.0, 32.0	93.4, 93.4	1.81, 1.80, 1.79	95.8
29	Ag-1.5 Cu-0.2 Ni	800	36.0, 35.9	25.5, 25.5	31.0, 31.0	93.2, 93.2	1.80, 1.80, 1.79	96.1

(a) Specimens were 0.050-inch-diameter wires.
(b) Specimens were air cooled from the annealing treatment.

TABLE C-6. FLEXURE-BREAKAGE PROPERTIES OF PURE SILVER AND THE SELECTED ALLOYS

Alloy	Composition, weight percent	Condition Before 700 F Exposure	Number of Bend Cycles to Failure After Exposure at 700 F for 2 Minutes[(a)]
0	Ag	Fully annealed, 1 hour 800 F	53, 71, 51, 65
		Worked 30 percent RA	50, 51, 45
2	Ag-1.5 Cu	Fully annealed, 1 hour 1000 F	65, 67, 73, 67
		Partially annealed, 1 hour 800 F	45, 42, 40, 44
		Worked 30 percent RA	39, 45, 42
5	Ag-0.5 Pd	Fully annealed, 1 hour 1200 F	45, 70, 44, 53
		Worked 30 percent RA	45, 50, 46
12	Ag-0.2 Ni	Fully annealed, 1 hour 1400 F	58, 67, 65, 66
		Worked 30 percent RA	41, 41
14	Ag-0.1 Cr	Fully annealed, 1 hour 1400 F	51, 60, 65, 46
		Partially annealed, 1 hour 1000 F	50, 49, 54, 54
		Worked 63 percent RA	62, 56
22	Ag-0.1 Be	Fully annealed, 1 hour 1200 F	42, 46, 43, 46
		Worked 15 percent RA	56, 61, 57, 64
23	Ag-1 Cu-0.2 Be	Fully annealed, 1 hour 1400 F	40, 35, 53, 35
		Partially annealed, 1 hour 800 F	37, 39, 38, 39
		Worked 15 percent RA	44, 44, 42, 37
26	Ag-1 Cu-0.1 Ni	Fully annealed, 1 hour 1200 F	58, 50, 54, 52
		Partially annealed, 1 hour 800 F	45, 46, 56, 55
		Worked 8 percent RA	51, 48, 51, 51
27	Ag-1 Cu-0.2 Ni	Fully annealed, 1 hour 1200 F	52, 55, 45, 65
		Partially annealed, 1 hour 800 F	43, 50, 43, 45
		Worked 30 percent RA	34, 33, 40, 31
28	Ag-1.5 Cu-0.1 Ni	Fully annealed, 1 hour 1200 F	61, 64, 57, 63
		Partially annealed, 1 hour 800 F	55, 48, 46, 51
		Worked 8 percent RA	32, 40, 42, 45
29	Ag-1.5 Cu-0.2 Ni	Fully annealed, 1 hour 1400 F	67, 77, 78, 94
		Partially annealed, 1 hour 800 F	51, 48, 45, 37
		Worked 8 percent RA	43, 48, 39, 42

(a) 0.050-inch-diameter wire specimens were bent over a 0.10-inch radius through an angle of 95 degrees. A tensile load of 330 grams (3.7-ksi stress) was applied to the specimens during the tests.

TABLE C-7. PROPERTIES OF 0.010-INCH-DIAMETER WIRE OF ALLOY 27 (Ag-1 Cu-0.2 Ni) IN SEVERAL CONDITIONS

Condition: Annealed for 1 Hour: Annealing Temperature, F	Condition: Annealed for 1 Hour: Annealing Atmosphere	Condition: Worked, percent Reduction in Area	Tensile Properties at 75 F: Ultimate Strength, ksi	Tensile Properties at 75 F: 0.2 Percent Offset Yield Strength, ksi	Tensile Properties at 75 F: Elongation, percent in 10 inches	Number of Bend Cycles to Failure Over a 0.050-Inch Radius[a]	Average Electrical Conductivity, percent IACS
			Worked Condition				
--	--	17	39.7, 39.9	37.5, 38.8	1.5, 1.5	57, 56, 57	--
			Annealed Condition Before 700 F Exposure				
600	Argon	--	35.7, 35.7	29.4, 29.9	13.3, 17.5	56, 65	--
800	Argon	--	31.9, 31.9	21.2, 21.6	26.8, 26.9	66, 64, 61	97.2
1000	Argon	--	31.0, 31.1	14.2, 14.1	31.2, 35.5	69, 75, 73	--
1200	Argon	--	30.5, 30.5	9.5, 10.8	31.2, 26.5	52, 54, 49	97.1
			After Exposure at 700 F In Air for 2 Minutes				
--	--	17	37.4, 37.3	33.1, 33.3	12.2, 11.5	54, 43, 56	--
600	Argon	--	34.3, 34.1	28.0, 27.7	17.3, 20.3	33, 35, 33	--
800	Argon	--	31.8, 31.9	21.4, 21.2	29.2, 30.2	54, 52, 55	--
1000	Argon	--	30.8, 30.6	14.2, 14.0	34.5, 34.3	53, 56, 50	--
1200	Argon	--	30.4, 30.6	11.1, 11.5	28.5, 30.2	41, 39, 39	--
600	Air	--	34.6, 34.3	27.6, 27.7	20.2, 19.2	61, 78, 67	--
300	Air	--	41.8, 42.5	32.4, 31.1	14.5, 17.0	61, 55, 57	100.1
1000	Air	--	42.6, 43.3	29.3, 30.5	15.5, 17.5	75, 78, 64	96.7
1200	Air	--	36.9, 35.5	20.6, 19.5	22.2, 21.5	69, 68, 69	--

(a) A tensile load of 100 grams (2.8-ksi stress) was applied to the wires during the bend tests.

APPENDIX D

TABULATION OF DATA ON SCALED-UP SILVER ALLOYS

TABLE D-1. DETAILED PROCEDURES USED TO PRODUCE HIGH-QUALITY INGOTS OF THE SCALE-UP ALLOYS

Elapsed Time, minutes	Procedure	Temperature of Melt, F
	Alloy 2 (Ag-1.4 Cu)	
0	Silver molten under hydrogen atmosphere	1,865
6	Hydrogen bubbled through the molten silver for 5 minutes	2,030
12	1.5 percent copper added to the molten silver	2,025
13	Molten alloy was stirred with a graphite rod for 2 minutes	2,025
15	Molten alloy held for 14 minutes under hydrogen atmosphere	2,000
29	Molten alloy stirred with a graphite rod for 2 minutes	2,000
31	Hydrogen bubbled through the molten alloy for 2 minutes	2,000
33	Hydrogen cover over melt displaced with argon	2,000
36	Heat tapped	1,945
	Alloy 12 (Ag-0.2 Ni)	
0	Silver molten under hydrogen atmosphere	1,925
7	Hydrogen bubbled through the molten silver for 6 minutes	2,065
14	0.2 percent nickel added to the molten silver	2,090
16	Molten alloy stirred with a graphite rod for 2 minutes	2,150
18	Molten alloy held for 10 minutes under hydrogen atmosphere	2,300

TABLE D-1. (Continued)

Elapsed Time, minutes	Procedure	Temperature of Melt, F
	Alloy 12 (Ag-0.2 Ni) (Cont'd)	
30	Melt stirred with a graphite rod for 3 minutes	2,300
33	Hydrogen bubbled through the molten alloy for 2 minutes	2,250
41	Hydrogen cover over melt displaced with argon	2,050
43	Heat tapped	1,970
	Alloy 27 (Ag-0.9 Cu-0.18 Ni)	
0	Silver molten under hydrogen atmosphere	2,000
4	Hydrogen bubbled through the molten silver for 5 minutes	2,000
11	1 percent copper added to the molten silver	2,020
12	Molten alloy stirred with a graphite rod for 4 minutes	2,000
22	0.2 percent nickel added to the molten alloy	2,200
23	Molten alloy stirred with a graphite rod for 3 minutes	2,275
26	Molten alloy held for 5 minutes under hydrogen atmosphere	2,200
31	Molten alloy stirred with a graphite rod for 2 minutes	2,200
33	Hydrogen bubbled through the molten alloy for 2 minutes	2,225
35	Hydrogen cover over melt displaced with argon	2,225
42	Heat tapped	1,965

TABLE D-2. TENSILE PROPERTIES OF MATERIALS SUPPLIED TO THE HUDSON WIRE COMPANY FOR SCALE-UP TO 19/42 CABLE

Material	Condition	Ultimate Tensile Strength, ksi	Elongation in Gage Length Indicated, percent	Reduction in Area, percent
Pure silver[a]	Worked unknown amount	29.9	23 (10 in.)	94
Alloy A[b]	Worked 60 percent RA	52.1	7 (1 in.)	91
Alloy B[b]	Worked 59 percent RA	38.3	10 (1 in.)	93
Alloy C[b]	Worked 59 percent RA	47.8	12 (1 in.)	90

(a) Pure silver was supplied as 0.062-inch-diameter wire.
(b) Alloys were supplied as 0.120-inch-diameter rod.

TABLE D-3. TENSILE PROPERTIES OF SCALED-UP ALLOYS BEFORE AND AFTER BEING INSULATED[(a)]

Wire	Composition, weight percent	Ultimate Tensile Strength, ksi: Single 42-Gage Strand	Ultimate Tensile Strength, ksi: 19/42 Cable	0.2 Percent Offset Yield Strength, ksi: Single 42-Gage Strand	0.2 Percent Offset Yield Strength, ksi: 19/42 Cable	Elongation in 10 Inches, percent: Single 41-Gage Strand	Elongation in 10 Inches, percent: 19/42 Cable
Before Insulation with Teflon							
Pure silver	99.99 Ag	26.1-23.2 (24.6)	22.9-23.6 (23.3)	17.7-14.7 (16.2)	16.3-15.9 (16.1)	19-12 (15.5)	8.0-9.6 (8.8)
Alloy A	Ag-1.5 Cu	35.6-35.4 (35.5)	35.4-35.2 (35.3)	28.7-27.7 (28.2)	29.5-29.3 (29.4)	17-17.6 (17.3)	20.4-17.6 (19.0)
Alloy B	Ag-0.2 Ni	31.6-31.2 (31.4)	30.8-30.8 (30.8)	22.8-20.4 (21.6)	18.8-18.9 (18.9)	16.6-19.6 (18.1)	23.0-21.6 (22.3)
Alloy C, fully annealed	Ag-0.9 Cu-0.18 Ni	33.4-33.4 (33.4)	33.3-33.4 (33.4)	25.5-24.0 (24.8)	24.1-24.7 (24.4)	18.5-22.2 (20.4)	24.4-28.0 (26.2)
Alloy C, partially annealed	Ag-0.9 Cu-0.18 Ni	36.7-37.1 (36.9)	36.7-36.7 (36.7)	30.5-30.8 (30.7)	31.1-31.1 (31.1)	12.2-9.6 (10.9)	17.8-18.8 (18.3)
After Insulation with Teflon (Teflon Removed from Test Specimens)							
Pure silver	99.99 Ag	22.9-21.7 (22.3)	16.5-20.9 (18.7)	18.9-15.9 (17.4)	13.0-12.5 (12.8)	4.4-6.0 (5.2)	15.4-11.4 (13.4)
Alloy A	Ag-1.5 Cu	35.7-35.4 (35.1)	33.9-32.5 (33.2)	26.2-26.0 (26.1)	25.5-26.8 (26.2)	21.2-19.4 (20.3)	20.0-13.0 (16.5)
Alloy B	Ag-0.2 Ni	30.4-30.4 (30.4)	29.7-29.7 (29.7)	20.7-21.1 (20.9)	19.4-19.4 (19.4)	19.1-18.9 (19.0)	30.2-26.4 (28.3)
Alloy C, fully annealed	Ag-1 Cu-0.2 Ni	33.1-33.6 (33.4)	33.0-33.0 (33.0)	24.3-24.0 (24.2)	23.7-24.4 (24.1)	21.0-21.4 (21.2)	29.8-27.0 (28.4)
Alloy C, partially annealed	Ag-1 Cu-0.2 Ni	35.7-35.8 (35.8)	35.3-35.3 (35.3)	29.6-30.6 (30.1)	30.1-30.1 (30.1)	14.4-13.6 (14.0)	17.8-19.2 (18.5)

(a) Average values of the duplicate tests are given in parenthesis.

TABLE D-4. EFFECT OF TEFLON INSULATION ON THE TENSILE PROPERTIES OF 19/42 CABLE[a]

Wire	Ultimate Breaking Load, pounds	Load at 0.2 Percent Offset Yield Strength, pounds	Elongation in 10 Inches
	Tested with Teflon Insulation Removed		
Pure silver	2.11-1.95 (2.03)	1.21-1.17 (1.19)	15.4-11.4 (13.4)
Alloy A	3.16-3.03 (3.09)	2.38-2.50 (2.44)	20.0-13.0 (16.5)
Alloy B	2.77-2.77 (2.77)	1.81-1.81 (1.81)	30.2-26.4 (28.3)
Alloy C, fully annealed	3.08-3.08 (3.08)	2.21-2.28 (2.24)	29.8-27.0 (28.4)
Alloy C, partially annealed	3.29-3.29 (3.29)	2.81-2.81 (2.81)	17.8-19.2 (18.5)
	Tested with Teflon Insulation		
Pure silver	3.94-4.30 (4.12)	1.62-1.50 (1.56)	32.8-37.0 (34.9)
Alloy A	5.14-4.75 (4.95)	2.86-2.85 (2.86)	49.0-35.0 (42.0)
Alloy B	4.93-5.02 (4.98)	2.10-2.08 (2.09)	55.2-53.4 (54.3)
Alloy C, fully annealed	4.96-5.04 (5.00)	2.50-2.55 (2.53)	49.0-50.7 (49.9)
Alloy C, partially annealed	5.12-4.78 (4.95)	3.07-3.12 (3.10)	42.0-30.0 (36.0)

(a) Average values of duplicate tests are given in parentheses.

TABLE D-5. ELECTRICAL PROPERTIES OF SCALED-UP ALLOYS AFTER BEING INSULATED WITH TEFLON[a]

Wire	Specific Electrical Resistivity, ohm-cm X10^6		Electrical Conductivity, percent IACS	
	Single 42-Gage Strand	19/42 Cable	Single 42-Gage Strand	19/42 Cable
Pure silver	1.68-1.68-1.68 (1.68)	1.66-1.67-1.67 (1.67)	103.4-102.9-103.4 (103.2)	103.4-103.8-103.1 (103.4)
Alloy A	1.77-1.77-1.77 (1.77)	1.81-1.82-1.81 (1.81)	97.4-97.4-97.4 (97.4)	95.3-94.7-95.3 (95.1)
Alloy B	1.73-1.73-1.72 (1.73)	1.69-1.71-1.69 (1.69)	99.8-99.8-100 (99.9)	102.2-101.2-101.7 (101.7)
Alloy C, fully annealed	1.83-1.83-1.83 (1.83)	1.82-1.81-1.82 (1.82)	94.1-94.3-95.3 (94.6)	94.7-95.2-94.8 (94.9)
Alloy C, partially annealed	1.81-1.82-1.83 (1.82)	1.80-1.83-1.83 (1.82)	95.2-95.0-94.1 (94.8)	95.7-94.5-94.5 (94.9)

(a) Average values of triplicate measurements are given in parentheses.