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ULTRASONIC SOLDERING OF ALUMINUM

by

J. Byron Jones and John G. Thomas

AEROPROJECTS INCORPORATED
West Chester, Pennsylvania

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ABSTRACT

Aluminum joints including one zinc-aluminum-silicon and nine tin-zinc-aluminum solder compositions were appraised for resistance to corrosion in an environment of 95°C, aerated, distilled water. The effect of pure zinc and pure aluminum metal over-sprays on extending the life of soldered aluminum joints was examined, with the aluminum spray proving to be effective. A soldered joint life up to about 1000 hours in the stipulated environment is indicated. Avenues for potential improvement in corrosion resistance of soldered aluminum joints are suggested.

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ULTRASONIC SOLDERING OF ALUMINUM

INTRODUCTION

This program on the joining of aluminum was undertaken to obtain information which could be applied specifically to ribbed aluminum components employed for heat exchange purposes. Originally initiated in March 1953, the work was oriented to investigating the feasibility of attaching aluminum ribs to aluminum tubes by means of ultrasonic fluxless soldering.

The soldering of aluminum has always been a difficult problem, chiefly because of the affinity of aluminum for oxygen, and the adherent oxide film which forms on aluminum surfaces exposed to air. Various soldering techniques and hundreds of solder alloys and solder fluxes have been developed in an effort to solve this problem.*

Conventional aluminum soldering techniques employ either a flux or the use of abrasive techniques to remove the oxide film from the aluminum. Both methods have their disadvantages. Flux which is a strong enough reagent to remove the oxide layer is usually corrosive, and the joint must be carefully washed after soldering to remove flux residue. However, even the most meticulous washing usually does not remove all traces of flux, and flux that remains usually becomes an agent for accelerated corrosion attack. Unremoved flux inclusions provide active corrosion sites when penetration occurs. Abrasive techniques of removing the oxide film from aluminum involve manual operations of brushing or scraping and represent a costly and time-consuming process. This technique generally does not produce a homogenous bond free of unbonded islands.

Ultrasonic soldering of aluminum, as developed by Aeroprojects, requires no flux to accomplish bonding. The pieces to be joined are heated to the melting point of the solder, usually below 390°C, and the solder alloy is flowed onto each piece. After the alloy has become molten, an ultrasonically active member delivers high intensity vibration into the solder in the areas to be bonded. The cavitation so produced in the molten solder fractures the tenacious aluminum oxide film and permits the solder to wet the aluminum. After the dross is removed from the molten solder, the pieces are positioned, clamped lightly together, and the solder is permitted to freeze. A metallurgical bond between the solder and the aluminum pieces is thus effected.

During the course of the initial program carried out by Aeroprojects for the du Pont Atomic Energy Division, ultrasonic soldering of aluminum was investigated with particular reference to the development of solder alloys

* See footnote, page 28

and soldering techniques which would provide maximum resistance to corrosion in the stipulated environment. Various tin-base and zinc-base solders were investigated, and solders were developed which retained about 25% of their original strength after 2700 hours of exposure in 95°C, low-conductivity, aerated, distilled water. Solders composed of 73% tin-23% zinc-4% aluminum and of 95% zinc-5% aluminum-silicon eutectic showed the most promise. The correlation of spectrographic analysis with the test results indicated that the presence of impurities in the solder elements probably adversely affected the corrosion resistance of the solders.

In addition under the earlier program, variables of ultrasonic exposure times and tinning temperatures were examined for their effect on corrosion rate, certain joint protective agents for ultrasonically soldered joints were considered, and a study of the corrosion mechanism was initiated.

This early work indicated potentialities in the further development of the ultrasonic fluxless soldering process for aluminum in several areas: utilization of high-purity solder constituents; optimization of element percentages in certain of the solder alloys; application of various protective coatings; and a rib geometry designed to extend the corrosion path.

SUMMARY

This program on the joining of aluminum was undertaken to obtain information which could be applied specifically to ribbed aluminum components employed for heat exchange purposes. The objective was to develop, by ultrasonic soldering techniques, a rib-to-tube joint which would have consistent residual strength of at least 200 to 400 pounds per inch of rib after exposure for 3000 to 6000 hours in a corrosion environment of 95°C, low-conductivity, aerated, distilled water.

The work involved the preparation and testing of lap specimens and rib specimens, using ultrasonic fluxless soldering techniques. Ten solder compositions were investigated to determine their resistances to corrosion in the specified environment. A variety of protective coatings were appraised for their effect on corrosion resistance. The rib geometry was varied, adding as little aluminum as possible, in an effort to provide a maximum corrosion path and maximum strength.

The following conclusions were drawn as a result of this work:

1. Certain of the specific aluminum-spray-protected solder joint configurations herein considered can be presently expected to withstand exposure to 95°C, aerated, distilled water for more than about 1000 hours.

2. It is possible that the zinc-aluminum-silicon solder would give long life in the absence of built-in stress, but stress relief may not be practicable.

3. In general, aluminum spray-coating of the soldered joints resulted in a substantial increase in life of the joint in the 95°C, aerated, distilled water environment.

4. Inferiority of the zinc-spray coating may result from a tendency of low-conductivity water to cause localized corrosion of the zinc.

5. The burnishing or coating post-aluminum-spray treatments were ineffectual in improving resistance to corrosion.

6. No correlation was evident between the rate of change in resistivity of the 95°C, aerated, distilled water bath and the rate of corrosion attack on the soldered aluminum specimens, but careful investigation of this phenomenon might expose interesting possibilities.

7. Because of the selective nature of the attack on the tin-zinc-aluminum solders, corrosive tendencies might be decreased by heat treatment and solid state diffusion near the eutectic temperature.

The following recommendations were made with regard to further investigation of ultrasonic soldering techniques for the intended purpose:

1. Brief exploration of the effect of stress relief of the zinc-aluminum soldered joints may be warranted.

2. Experimental examination of the effect of heat-treating the tin-zinc-aluminum soldered joint is worthy of consideration.

3. Preliminary appraisal of M-257 aluminum alloy in soldered joints should be considered.

DISCUSSION

OBJECTIVE OF STUDY

The objective of the program was to develop a rib-to-tube joint which would have consistent residual strength of at least 200 to 400 pounds per inch of rib after exposure for 3000 to 6000 hours in a corrosion environment of 95°C, low-conductivity, aerated, distilled water.

Several experimental approaches were used in an effort to develop such joints by means of ultrasonic fluxless soldering techniques. The composition of solder alloys which had appeared promising under the earlier program was systematically varied in order to optimize the percentages of constituents. High-purity solder elements were used so that deleterious effects of impurities might be minimized. Ultrasonic soldering techniques were refined. A variety of protective coatings were investigated for their effects on corrosion resistance. The rib geometry was varied, using as little aluminum as possible, in an effort to provide a maximum corrosion path and maximum strength.

EXPERIMENTAL PROCEDURES

Exploration of the several parameters listed above was accomplished by the preparation and test of ultrasonically soldered lap and rib specimens. Because of the difficulty of devising and carrying out a satisfactory strength test for the soldered rib specimens economically, lap specimens for tension shear test provided a convenient means for evaluating strength decay during exposure in the corrosion environment.

Equipment and Materials

The lap specimens were soldered with Aeroprojects standard "Sonobond" equipment, which consists of an ultrasonic soldering head and heating platen (see Figure 5) and a 100 r-f watt ultrasonic generator. The generator supplies r-f power to the transducer located in the movable soldering head; the transducer, operating at a frequency of 20 kc, converts the electrical power into acoustical power and transmits this power through a coupling into the heated soldering tip of 15/16-inch diameter, and thence into the area to be soldered. The platen supplies the heat required for heating the work pieces to the proper soldering temperature.

To provide a higher unit intensity of ultrasonic energy and to achieve an ultrasonic soldering tip geometry suitable for the tinning of the rib and sheath joint areas, the experimental ultrasonic soldering head shown in Figure 6 was used. This unit proved to be very effective in tinning a ribbon-like area on a sheet at a satisfactory rate. It was also powered by the 100 r-f watt ultrasonic generator.

One primary phase of the program consisted of the appraisal of three groups of solder alloys, selected on the basis of the most promising results from the earlier investigation. For the first group, the 73% tin-23% zinc-4% aluminum solder was used as a base, and the zinc and tin percentages were varied, maintaining a constant aluminum content. The same base solder was used in the second group and the aluminum content was varied, with a reasonable soldering temperature limiting the aluminum content. The third type of solder was a 95% zinc-5% aluminum-silicon alloy, the aluminum-silicon being the eutectic composition. The solder compositions are listed below:

Solder	Composition	Approximate Melting Point*
Group A		
A-1	64% Sn, 32% Zn, 4% Al	350°C
A-2	67% Sn, 29% Zn, 4% Al	350°C
A-3	70% Sn, 26% Zn, 4% Al	360°C
A-4	76% Sn, 20% Zn, 4% Al	375°C
A-5	79% Sn, 17% An, 4% Al	375°C
A-6	82% Sn, 14% Zn, 4% Al	375°C
Group B		
B-1	73% Sn, 23% Zn, 4% Al	365°C
B-2	60% Sn, 35% Zn, 5% Al	365°C
B-3	58% Sn, 36% Zn, 6% Al	380°C
Group C		
C-1	95% Zn, 4.4% Al, 0.6% Si	382°C

The tin used in preparing the above solders was Extra-High-Purity tin obtained from the Vulcan Detinning Company, Sewaren, New Jersey. This metal was stated by the supplier to have the following impurities, based on laboratory analysis:

*Jares, V., "Constitution of Alloys of Aluminum, Zinc, and Tin, and Aluminum, Zinc, and Cadmium." Transactions of the American Institute of Mining and Metallurgical Engineers, Institute of Metals Division, 1927, pp. 67-81 (Preprint No. 1588-E, October 1926).

Lead	0.0001%
Iron	0.0001%
Copper	Trace (less than 0.0001%)

No other metals were detected in the tin.

The zinc was obtained from the New Jersey Zinc Company, and spectrographic analysis by the W. B. Coleman Company of Philadelphia revealed the following impurities:

Copper	0.0003%	Tin	<0.0005%
Lead	0.001%	Magnesium	0.002%
Iron	0.0004%	Cadmium	<0.001%

The following elements were not found in the zinc: aluminum, antimony, barium, beryllium, bismuth, boron, calcium, chromium, cobalt, columbium, gallium, germanium, gold, manganese, molybdenum, nickel, platinum, silicon, silver, sodium, strontium, tellurium, titanium, tungsten, vanadium, and zirconium.

The alloying aluminum was obtained from commercial 2S sheet.

In preparing the solders of Group A and Solder B-1, a master alloy was prepared under argon, consisting of 78% zinc and 22% aluminum. To this master alloy were added sufficient tin and zinc to obtain the proper composition for each solder. Solders B-2, B-3, and C-1 were alloyed directly from the pure metals.

Several other solder alloys prepared under the earlier program were significant because results of corrosion tests on rib specimens prepared with these earlier solders were received and evaluated during the current program. These solder alloys had the following compositions:

100% tin	Prepared from reagent grade tin
99% tin-1% magnesium	Prepared from reagent grade tin
85% tin-5% zinc	Prepared from reagent grade elements
73% tin-23% zinc-4% aluminum	Prepared from reagent grade elements
73% tin-23% zinc-4% aluminum	Prepared from high-purity elements
95% zinc-5% aluminum	Prepared from reagent grade elements
95% zinc-5% aluminum-silicon	Prepared from reagent grade elements
95% zinc-5% aluminum-silicon	Prepared from high-purity elements

The reagent grade tin used in these solders was guaranteed by the manufacturer to have an analysis falling within the maximum limits of impurities according to A. C. S. specifications:

Arsenic	0.0003%
Copper	0.002%
Iron	0.01%
Lead	0.01%
Zinc	0.01%

The high-purity tin was obtained from the A. D. Mackay Company of New York City; spectrographic analysis by the W. B. Coleman Company revealed the following impurities:

Aluminum	0.004%
Copper	0.0002%
Iron	0.002%
Lead	0.005%

The following elements were not found: antimony, arsenic, barium, beryllium, bismuth, boron, cadmium, calcium, chromium, cobalt, columbium, gallium, germanium, gold, magnesium, manganese, molybdenum, nickel, platinum, silicon, silver, sodium, strontium, tellurium, titanium, tungsten, vanadium, zinc, and zirconium.

The reagent grade zinc was Horsehead Special type obtained from Platt Bros., Waterbury, Connecticut, and found from spectrographic analysis by the W. B. Coleman Company to contain the following impurities:

Copper	0.0002%
Cadmium	0.002%
Chromium	0.0005%
Iron	0.001%
Lead	0.005%
Manganese	0.0001%
Nickel	0.0005%
Silver	0.0001%
Tin	0.0004%

Elements not found were as follows: aluminum, antimony, arsenic, barium, beryllium, bismuth, boron, calcium, cobalt, columbium, gallium, germanium, gold, magnesium, molybdenum, platinum, silicon, sodium, strontium, tellurium, titanium, tungsten, vanadium, and zirconium.

The high-purity zinc, obtained from the New Jersey Zinc Company, was found by the W. B. Coleman Company to contain:

Cadmium	0.001%
Copper	0.0005%

Iron	0.005%
Lead	0.002%
Magnesium	0.002%
Tin	0.001%

Elements not found were: aluminum, antimony, arsenic, barium, beryllium, bismuth, boron, calcium, chromium, cobalt, columbium, gallium, germanium, gold, manganese, molybdenum, nickel, platinum, silicon, silver, sodium, strontium, tellurium, titanium, tungsten, vanadium, and zirconium.

The aluminum used was from commercial 2S sheet, and the aluminum-silicon was the eutectic composition.

Test Specimens

Lap specimens for tension-shear strength testing were prepared from 0.072-inch-thick 24S-T3 Alclad aluminum alloy in accordance with the configuration shown in Figure 1. The 24S-T3 Alclad aluminum was used for these specimens rather than the 2S aluminum specified for the rib specimens, because the harder alloy was required to provide adequate strength to insure fracture in the solder bond during the first 500-1000 hours of corrosion exposure. The 2S cladding on the 24S alloy simulated joint characteristics on 2S aluminum.

The procedure for soldering the lap specimens was as follows: The aluminum tabs were washed in methyl-ethyl ketone or acetone and were placed on the soldering platen, which had been previously heated to a temperature slightly above the liquidus of the solder alloy. The prescribed solder was placed on the tabs, and the active ultrasonic soldering tip was lowered and held in contact with the solder for a total exposure time of 20 seconds. The tinned areas of the two tabs were then slid together. It was noted that a skin formed on each of the tinned tabs while the solder alloy was still in the molten state. This skin was sufficiently tough to prevent good bonding unless it was removed or disrupted by moving the tinned areas of the tabs after placing them in contact. The best technique consisted of placing the two pieces in contact while the solder was liquid and briefly sliding the tabs back and forth with an excursion of 1/8 to 5/16 inch, then clamping the tabs together lightly and permitting the solder to freeze. About 150 tab specimens were prepared with each of the ten primary solders used in the program.

Thirty additional specimens of each solder were prepared, using particular care to remove all traces of surface film which formed on the solder after tinning and before assembly. These tabs were tinned in the manner described above, but after tinning the solder was wiped off, fresh solder was applied, and the pieces were quickly and carefully slid together to expel surface film on the solder.

Three types of rib specimens were prepared for corrosion testing. During the earlier program, trapezoidal ribs of 2S aluminum had been ultrasonically soldered to channel sections of 2S aluminum in accordance with the configuration and dimensions shown in Figure 2. The solders used for these trapezoidal ribs consisted of 100% tin, 95% zinc-5% aluminum, 95% zinc-5% aluminum-silicon, 85% tin-15% zinc, and 99% tin-1% magnesium, all of which were prepared from reagent grade elements.

The specimens were made by tinning the sheet with the special flat ribbon soldering unit shown in Figure 6. The base of the rib was also pretinned, and, while the solder on both pieces was molten, the rib was placed on the channel section and slid back and forth briefly to break up the oxide skin on the exposed solder areas. Clamping force was applied to the ribs over the tinned zone with spring clamps, and the solder was allowed to freeze. Exposed solder of some of these rib specimens was left unprotected, while others were given spray-metal coatings of zinc or aluminum.

Also during the earlier program, rib specimens prepared with solder alloys of 73% tin-23% zinc-4% aluminum and of 95% zinc-5% aluminum-silicon, made of both reagent and high-purity grade elements, were assembled and delivered to Savannah River for corrosion tests. These specimens had the configuration shown in Figure 3. It was felt that the trapezoidal ribs, with a base width of 0.070 inches, offered too short a corrosion path (0.035 inches) to provide an effective joint in the stipulated environment, so the folded type of rib shown in Figure 3 was evolved. This folded type of rib offered a total base width of 0.300 inches while retaining the same rib cross-sectional area (0.0045 square inches) as the trapezoidal ribs.

These specimens were soldered in the same manner as that described for the trapezoidal rib assemblies. Both rib and channel were pretinned with the flat ribbon soldering unit shown in Figure 6, and the rib was slid back and forth briefly in position to break up any surface layer which had formed on the exposed solder. Clamping force was applied with spring clamps and the assembly was allowed to solidify. In order to investigate the effect of protective coatings, several of each type of specimen were left bare, some of each were coated with silicone grease, some were metal-sprayed with aluminum, some metal-sprayed and then coated with silicone grease, and some were metal-sprayed and burnished.

It was later determined that this folded type of rib offered a third path for corrosion attack--in the center of the base as well as along each edge--so a new rib-channel configuration with a machined rib having a solid base (See Figure 4) was prepared for testing each of the ten primary solder alloys (described above) used on the lap specimens under this program. The cross-sectional area of these ribs was 0.0046 to 0.005 square inches, only slightly greater than that of the folded ribs. The channel pieces on which these ribs were mounted were made 2-3/8 inches long, while the ribs were 2 inches long, thus providing a 3/16-inch overhang of the channel beyond the rib on each end.

Soldering of the ribs to the channels was accomplished in the following manner: The channel was ultrasonically tinned through a slotted stainless steel template guide at the prescribed temperature for each solder, using the flat ribbon soldering unit shown in Figure 6. The rib base was tinned in the same manner. All solder was then wiped clean from both parts and fresh solder was applied. While still at elevated temperature, the rib was placed on the channel and slid back and forth a few times to break up oxide formation on the solder surface. The pieces were then clamped together and allowed to solidify. The ultrasonic tinning time was 60 seconds on the channel and 60 seconds on the rib.

To permit evaluation of various protective coatings, 21 rib-channel specimens were made with each solder, with three specimens for each of seven different conditions, as follows:

A. Narrow-base rib specimens (0.300 inch)

1. Bare ribs
2. Aluminum-sprayed
3. Aluminum-sprayed and burnished
4. Aluminum-sprayed and coated with "Dow" DC-7 silicone grease
5. Aluminum-sprayed and painted with du Pont "Butanol" dispersion paint
6. Aluminum-sprayed and painted with "Metco" silicon-aluminum paint

B. Wide-base rib specimens (0.400 inch)

1. Bare ribs only

The aluminum spraying was accomplished by the Metallizing Engineering Company, Long Island City, New York. The following procedure was used: Each side of the rib was first sandblasted under a masking fixture with "Metcolite" F, an aluminum oxide compound, for about 15 seconds. The specimen was then immediately placed on a copper block which had been preheated to a temperature of 120°C for solder alloy A-1 and 150°C for all other solders. About 30 seconds were allowed for the specimen to reach the elevated temperature of the block, and no more than 2 or 3 minutes were allowed to elapse after sandblasting and before spraying. The spray gun, "Metco" Type 4A, was fed with "Metco" 1/8-inch-diameter aluminum wire at a rate of about 7 feet per minute, and the gun was held approximately 7 inches from the specimen. One pass was made across each side of the rib from left to right and a second pass from right to left, each pass being about 1-1/2 seconds duration. By rotating the revolving table supporting the copper block, both sides and both ends of the rib could be sprayed without handling the specimens. The thickness of the sprayed coat was in the range of 0.003-0.005 inch.

The burnished specimens were burnished with a wire wheel driven by a "Handee" tool. The DC-7 silicone coating was wiped on. The "Metco" silicon-aluminum coating and the du Pont "Butanol" coating were painted on and air dried.

Corrosion-Strength Tests

The corrosion resistance of the lap specimens to low-conductivity, aerated, distilled water at 95°C was evaluated by appraising the tensile-shear strength decay of the specimens and by observing the corrosion penetration of the solder in the lap joints.

Lap specimens prepared with each of the ten solders were exposed in a corrosion bath for a total of 3638 hours. For each solder, 100 specimens were suspended from glass rods in a glass beaker of distilled water. Air was delivered into the bottom of the beaker through a fritted glass disk fitted with a glass bubbler tube. The protruding end of the tube was connected to an air-pressure reducing valve to maintain the air supply to that beaker. All ten beakers were placed in a large, open, temperature-controlled, heated vessel filled with water, which was maintained at a constant temperature of 95° ± 2°C. High-pressure air was manifolded to the pressure controller for each beaker, and air was bubbled through the distilled water in the beakers continuously.

It had been specified that the water in the beakers be held at a resistivity in excess of 100,000 ohms at room temperature. In order to accomplish this, the resistivity was monitored by means of a "Serfass" conductance bridge (Industrial Instruments Model No. RC-M15) with a dipping conductivity cell having a cell constant of approximately 1.0. Preliminary checks indicated that the resistivity of distilled water at 95°C is about 40-45 percent of the resistivity recorded at room temperature; i.e., a resistivity reading of 100,000 ohms at room temperature was indicated to be approximately equivalent to 40,000 ohms at 95°C. Whenever the resistivity of the water (initially 500,000 to 600,000 ohms at room temperature) approached 40,000 ohms at 95°C, fresh water was added or the water in the beaker was completely changed.

Before exposure in the corrosion bath, ten tab specimens prepared from each type of solder were tested to failure in tension-shear. The tests were conducted in a standard

Young hydraulic testing machine equipped with self-aligning jaws. The loading rate was maintained reasonably constant at approximately 600 pounds per minute until failure occurred. At stated intervals during the test, four standard specimens and three oxide-free specimens of each solder type were removed from the corrosion bath and tested in the same manner.

After each group of tests, the fractured specimens were examined to determine the extent of corrosion penetration into the soldered area. The solder area on the fractured joint was photographed on 35 mm film. An enlarged print of the film made it convenient to measure the total solder area and residual unattacked area with a planimeter. The percentage of unaffected area was then readily determined for each group of specimens.

Metallographic studies were also made on the lap specimens. Two control specimens for each type of solder were sectioned, mounted, polished, and etched with "Nital" for microscopic examination. Whenever specimens were removed from the corrosion bath for strength tests, an additional specimen was removed and was sectioned, polished, and etched for microscopic examination, so that the strength data could be correlated with metallographic appraisal.

To determine the effect of the stipulated corrosion environment on the solders alone, without the presence of aluminum, several samples of bulk solders were tested at Savannah River Laboratory: 100% tin, 85% tin-15% zinc, 83% tin-15% zinc-2% aluminum, 43% tin-55% zinc-2% aluminum, 99% tin-1% magnesium, 99.7% tin-0.3% magnesium, 80% zinc-20% tin, and 95% zinc-5% aluminum. Each sample is reported to have been placed in a 100-milliliter flask with distilled water at 70°C constantly flowing through. Before the test was started, each sample was degreased with ethyl alcohol. At intervals during the test, the samples were removed from the bath, dried with alcohol, and visually examined for corrosion effects.

Specimens of all three types of rib-channel configuration prepared under the program were exposed to a corrosion environment at Savannah River Laboratory. The corrosion bath consisted of deionized, aerated, distilled water which was maintained at a temperature of 95°C. The resistivity of the water was carefully monitored so that it would not fall below 100,000 ohms at room temperature. Periodically the specimens were removed from the bath and examined. Since no satisfactory strength test was then available for rib specimens of the configuration and dimensions shown in Figures 2, 3, and 4, the resistance of the specimens to corrosion was evaluated in terms of the exposure time required for the rib to separate from the channel.

Two groups of the trapezoidal rib specimens were also given corrosion tests at Battelle Memorial Institute. These included specimens soldered with 85% tin-15% zinc and with 99% tin-1% magnesium; for each solder, ribs were tested as soldered, with an aluminum-spray coating, and with a zinc-spray coating. Battelle is reported to have used low-conductivity, distilled water maintained at a temperature of 95°C and with an initial resistivity in excess of 500,000 ohms. The conductivity was not monitored daily, but once a week the test was interrupted and the sample was removed from the bath, cleaned, and examined; at the same time the flask was cleaned and refilled with fresh water. No makeup water was added during the week. No aeration was provided, but the surface of the bath was exposed to the atmosphere. Corrosion resistance was determined by the exposure time required for the rib and channel to separate.

At the conclusion of the test at Battelle, these rib specimens were returned to Aeroprojects for metallographic examination. The bare and the aluminum-sprayed specimens, which were still intact, were sectioned, polished, etched with a 0.5% hydrofluoric acid solution, and examined under a microscope.

TEST RESULTS

The results of the corrosion-strength tests on the lap specimens are presented graphically in Charts 1 through 10, which show the decrease in strength from 0 hours through 3638 hours of exposure. The scatter within each group of four standard specimens, the average strength of the standard specimens, and the average strength of the oxide-free specimens is shown for each time interval of testing. The upper curve on each of these charts shows the progressive decay in unaffected solder area during exposure. Chart 11 presents a summary of average strength of lap specimens for all solders at selected exposure times.

Photomicrographs were made of cross sections of lap specimens with representative solders A-1, A-6, B-1, and C-1: before exposure and after 182, 422, 902, and 3638 hours of corrosion exposure. These micrographs, presented in Figures 7, 8, 9, and 10, show the changes in the metallurgical structure of the joints during the exposure period.

Figure 11 shows the appearance of fractured specimens prepared with solder alloy B-1 after 182, 422, and 902 hours of corrosion exposure.

It was noted that the resistivity of the corrosion bath was monitored continuously throughout the test. Resistivity measurements for each separate bath are plotted in Charts 12 through 21, in anticipation that some correlation could be made between the rate of corrosion in the lap specimens and the change in resistivity of the water. In each case, the lower curve represents actual resistivity readings taken during the test. When the water in the bath was changed, at points indicated by arrows on the charts, there were resulting variations in the temperature of the bath; thus resistivity readings immediately following water changes are not recorded on the graphs.

The upper curves of Charts 12 through 21 plot the rate of decrease in resistivity of each bath between water changes. These data were obtained by calculating the total decrease in resistivity, in ohms, from each peak in the curve to the subsequent low point, and dividing by the total number of elapsed hours during that period. No correction has been made for additions to the water in the bath between water changes.

The results of corrosion tests at Savannah River Laboratory on the bulk solders are summarized in Table I. The rate of corrosion of these solders was determined from the total loss of weight during the specified test period, and comments are presented regarding the general appearance of the solders after exposure.

Tables II, III, and IV present data resulting from corrosion tests at Savannah River Laboratory on the trapezoidal rib specimens soldered with 100% tin, 95% zinc-5% aluminum, and 95% zinc-5% aluminum-silicon. The total time to failure is noted in each instance. Tables V and VI present comparative results from tests at Savannah River Laboratory and at Battelle Memorial Institute on trapezoidal rib specimens soldered with 85% tin-15% zinc and with 99% tin-1% magnesium solder alloys. In several instances (noted by the plus sign) the test was stopped before the specimen had failed. A comparison of results on these trapezoidal rib specimens is graphically shown in the bar graph of Chart 22.

Typical photomicrographs of the trapezoidal rib specimens after exposure at Battelle are presented in Figures 12 and 13. These micrographs show a cross section through the fillet area of the joints. For comparison, Figure 14 shows a cross section of the fillet area of a rib channel assembly soldered with a 76% tin-20% zinc-4% aluminum alloy. This micrograph was prepared after the assembly had aged at room temperature for 84 days.

The results of corrosion tests on the folded rib specimens prepared with 95% zinc-5% aluminum-silicon and with 73% tin-23% zinc-4% aluminum, of both reagent grade and high-purity elements, are presented in Tables VII and VIII.

Data for the final group of rib specimens, prepared from machined ribs and covered with various protective coatings, are presented in Tables IX through XVIII inclusive, and the average exposure times to failure for the various types of specimens are summarized in the bar graph of Chart 23.

APPRAISAL OF RESULTS

Lap Specimens

From an examination of the strength data on the lap specimens presented in Charts 1 through 10, it is apparent that all of the solders showed a rapid decline in strength during the first 500-1000 hours of corrosion exposure and that no significant decrease in strength occurred with any of the solders after the first 1000 hours.

The initial decrease in strength corresponds with the apparent decay in unattacked area of the solder, as shown in the upper curves of Charts 1-10. Associated with the general decrease in uncorroded area of the overlap, a form of darker colored, ring-shaped bands or lines was observed around the general center of the unattacked zone. These bands are evident in the representative photographs of Figure 11.

All solders of the "A" and "B" groups generally showed an average strength of 500-700 pounds during the last 2600 hours of testing. From Chart 11, which summarizes the strengths of all ten types of soldered joints at selected corrosion exposure times, it appears that the best solders were A-4 and A-5. The specimens incorporating solder A-4 in particular showed little scatter throughout the 1000-3600 - hour range, and the strengths were slightly higher than those of other solders in this group. Solder A-4 also showed the lowest rate of joint penetration as revealed in the curve showing the percent unaffected area versus time.

Increasing the aluminum content (Group B) of the tin-zinc-aluminum ternary reduced the rate of penetration, but resulted in increased scatter in specimen strength during exposure. With 6% aluminum (solder B-3), considerably more scatter was evident in the strength data, and the strength was slightly lower than that of solders B-1 and B-2.

Examination of the corrosion specimens under polarized light aided separation and identification of phases in the ternary solder alloys. Solders of the tin-zinc-aluminum system exhibited an appreciable quantity of primary aluminum in the structure, suggesting a high rate of solution from the parent material resulting from the ultrasonic action. Attack on these solders tended to be restricted to the needles of primary zinc or zinc-tin and to the zinc-rich constituent of the eutectic, resulting in a mode of corrosion similar to intergranular attack (Figures 7, 8, 9). This selective corrosion behavior of the alloys may help to explain the distribution of the strength decay curves. Propagation of corrosion along the zinc-rich network of the solder probably proceeds simultaneously from the edges of the soldered area toward the center and is accompanied by an expected decrease in resistance to fracture. The area of the unaffected portion of the joint shown in Figure 11 appeared to reach a zero value at approximately 900 hours, although the test specimens retained about 25% of their original strength. In view of the mode of attack already described, it would appear that the primary selective attack is accompanied by a secondary attack, proceeding at a somewhat slower rate, along the same zinc-rich network and resulting in a honeycombed structure, the specimens retaining moderate strength by virtue of the unaffected primary aluminum phase. The apparent constant strength at extended exposure probably is a result of the "bridging" effect of the primary aluminum.

The tests with lap specimens prepared with 95% zinc-5% aluminum-silicon solder had been conducted in anticipation that the use of high-purity zinc in the alloy (less than 0.001% lead) would significantly reduce scatter and result in more consistent strength values than had been achieved in the earlier program with less pure zinc. Generally higher average strengths are shown for solder C-1 than were recorded for previous tests with the same alloy but made with zinc indicated to contain 0.002% and 0.005% lead. However, excessive scatter in strength was evident throughout the test. In general, solder C-1 appeared more susceptible to corrosion than either the "A" group or "B" group solders.

The mode of attack on the ternary zinc-aluminum-silicon solder appears to be different from that on the tin-base solders. Solution of aluminum from the surface of the specimen while soldering was not appreciable. Examination of the specimens revealed that the solder tended to crack upon prolonged exposure. The appearance of the specimens strongly suggests stress corrosion cracking (Figure 10).

The oxide-free specimens of all solders had been prepared in anticipation that careful fabrication techniques might produce more corrosion-resistant specimens. However, the average strengths of these specimens were generally lower than the average strengths of the standard specimens. It was suspected that some aluminum cladding from the parent material was dissolved in the solder during the ultrasonic tinning operation. By wiping off the solder and replacing it, the aluminum content in the solder may have been reduced. This however, is not reflected in the greater aluminum content of the "B" group of solders.

It had been anticipated that some correlation could be made between the change in resistivity of the corrosion baths and the strength and metallurgical data. Examination of the curves of Charts 12 through 21 failed to reveal any such correlation. In every instance, the rate of change in resistivity decreased from the beginning of the test to the end, but this can probably be explained on the basis that the number of specimens remaining in the bath became progressively less throughout the test.

Bulk Solders

The corrosion tests on the bulk solders (Table I) indicated the most promising to be 100% tin and the tin-zinc binary alloys. The tin-magnesium solders showed severe intergranular attack after only a few hours of exposure, and the zinc-aluminum alloy had only fair resistance to attack. In terms of corrosion rate, the pure tin showed the least loss in weight. It was recognized, however, that the corrosion resistance of these bulk solders did not necessarily reflect their behavior when incorporated in a soldered aluminum joint.

Rib Specimens

Although the 99% tin-1% magnesium solder was the most readily corroded of the bulk solders tested, bare trapezoidal rib specimens prepared with this solder showed more resistance to corrosion in tests at the Savannah River Laboratory than similar specimens soldered with other tin-and zinc-base solders. None of the bare rib specimens proved to have sound joints in the specified environment (Tables II, III, IV, V, and VI). The zinc coating in every instance accelerated corrosion of these specimens, while the aluminum spray provided a protective coating which markedly delayed corrosive action, as is evident from the bar graph of Chart 22.

Inconsistent results are noted in a comparison of the corrosion tests conducted at Savannah River Laboratory and those at Battelle Memorial Institute on solders of 85% tin-15% zinc and 99% zinc-1% magnesium (Tables V and VI). In all instances with the bare and aluminum-sprayed ribs, the Savannah River specimens failed in a considerably shorter time than the Battelle specimens. The test at Battelle was discontinued after 4000 hours, at which time the specimens showed only slight separation of rib from channel at the extremities of the joint. Since the samples for both series of tests were from the same group, the discrepancy could not be explained on the basis of the solder, the base material, or the soldering techniques. The only known difference in testing techniques was that Savannah River provided aeration in the corrosion bath water, while Battelle merely exposed the surface of the water to the air.

Metallographic examination of the Battelle specimens after exposure provided no clue to the long corrosion life of these specimens. Typical micrographs are shown in Figures 12, 13, and 14. In all three specimens, it was noted that there were differences in composition of the aluminum rib and the aluminum channel material, both of which had been purchased as 2S material. The rib structure contained profuse small particles which have been identified as silicon, suggesting that the aluminum alloy may have been 32S rather than 2S.

The solder area on all specimens exhibited separation along the interface between the solder and the channel at the extremities of the joint. The solder structure for both solders revealed modest intergranular attack progressing from the outside fillet into the joint. The solder bond was extremely thin in some locations, occasional contact between rib and channel being apparent. One of the specimens soldered with 85% tin-15% zinc fractured during sectioning. Another specimen was separated with pressure. In both instances, the fracture surface exhibited the dark, unreflective appearance of fracture surfaces on the tab specimens previously described (cf. Figure 11). For comparison with these specimens, a section of a rib-channel assembly soldered with 76% tin-20% zinc-4% aluminum is shown in Figure 15. In this instance, the elevated temperature required for soldering resulted in a fully annealed structure in both rib and channel and consequent intergranular penetration by the solder into the 2S aluminum.

On the basis of these observations, it was indicated that the Battelle specimens exhibited the same corrosion characteristics as the Aeroprojects standard lap specimens, and that these results differ from those of the Savannah River Tests.

The corrosion tests on the folded rib specimens (Tables VII and VIII) revealed a short corrosion life for all of these specimens. Since the original specimens, 12 inches long, had been sheared into 2-inch lengths before immersion in the corrosion bath, the ends of the samples were not protected, and the effect of the protective coatings could not be evaluated. No significant difference could be detected between the results for solders prepared with high-purity elements and those prepared with reagent grade elements. These tests made it evident that sound joints could not be produced with folded ribs of this type, since the void in the center of the rib base provided an additional path for corrosion attack.

The final group of rib specimens had therefore been made with solid-base machined ribs. The results of tests on these machined rib specimens (Tables IX through XVIII) reveal a number of anomalies for which no immediate explanation is apparent. For example, the wide-base rib specimens with the longer corrosion path would be expected to fail later than the narrow-base specimens, but in practically every instance the reverse was true. Furthermore, considerable scatter is evident in the time to failure of similar specimens, some lasting three to four times as long as others prepared with the same solders and under the same conditions.

However, from the graphic summary of results presented in Chart 23, several trends confirm the results of tests previously discussed. It is evident that aluminum spray offers a definite protection to the soldered joints. In practically every instance, the aluminum-sprayed ribs showed a longer corrosion life than any of the other types tested; an additional coating over the metal spray appeared to weaken the spray coating. This superiority confirms the results of corrosion tests on the trapezoidal rib specimens.

With regard to solder composition, the range of 76% tin-20% zinc-4% aluminum to 79% tin-17% zinc-4% aluminum appears to have optimized the corrosion resistance of the tin-zinc-aluminum alloys. This generally confirms the results of corrosion tests on the lap specimens as presented in Chart 11. It will be noted that rib specimens were prepared using the so-called oxide-free technique in which the original solder was wiped off and fresh solder was applied. The rib test results should therefore compare with the oxide-free lap specimens. Aluminum oxide in greater quantity would affect the result.

Solder alloy C-1 showed the longest corrosion life of all the solders under nearly every condition. This was also true for certain single specimens in the corrosion tests on lap specimens, although the averages were lower than those of other solders in the lap specimen series.

The results of corrosion tests on the channel specimens with various rib configurations suggest a stress corrosion phenomenon. Stresses were probably introduced into the solder bond by non-uniform contraction of the rib channel members from soldering temperatures. In such a situation, the wide-flange ribs would create higher residual shear stresses in the solder than the narrow-flange or trapezoidal ribs, and any advantage gained by increasing the effective corrosion path would tend to be offset by a higher stress concentration.

* Reference from page 10
Development of the ultrasonic soldering process was first undertaken by Aeroprojects for the Frankford Arsenal. Results of these preliminary efforts are reported in Aeroprojects Incorporated, "The Soldering of Aluminum and Its Alloys," Research Report No. 54-8, January 1954, Contract No. DA-36-034-ORD-1401 for Pitman-Dunn Laboratories, Frankford Arsenal, Department of the Army, Philidelphia, Pennsylvania.

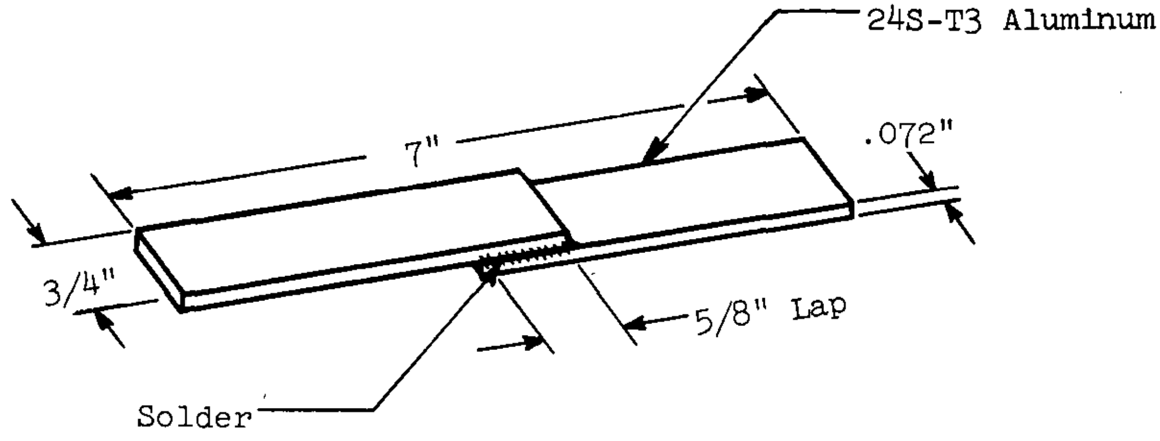


FIGURE 1

LAP SPECIMEN CONFIGURATION

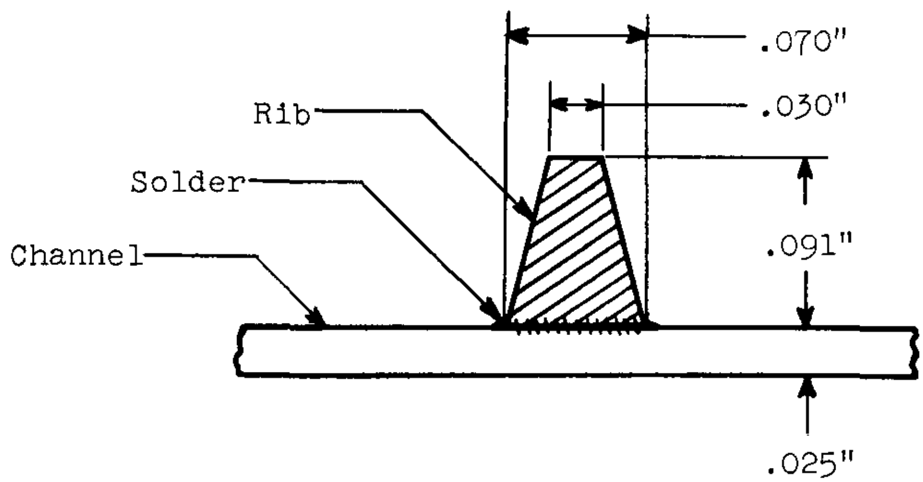


FIGURE 2

TRAPEZOIDAL RIB-CHANNEL CONFIGURATION

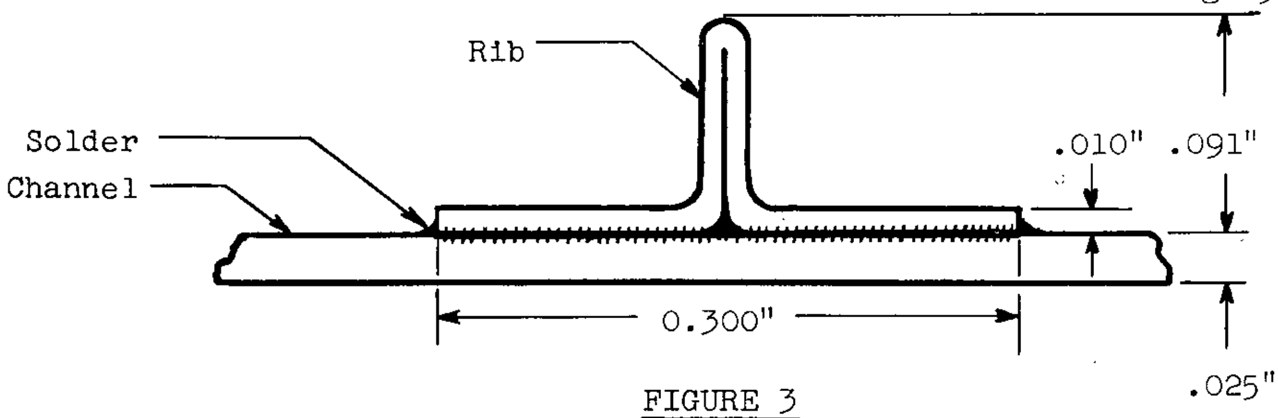


FIGURE 3

FOLDED RIB-CHANNEL CONFIGURATION

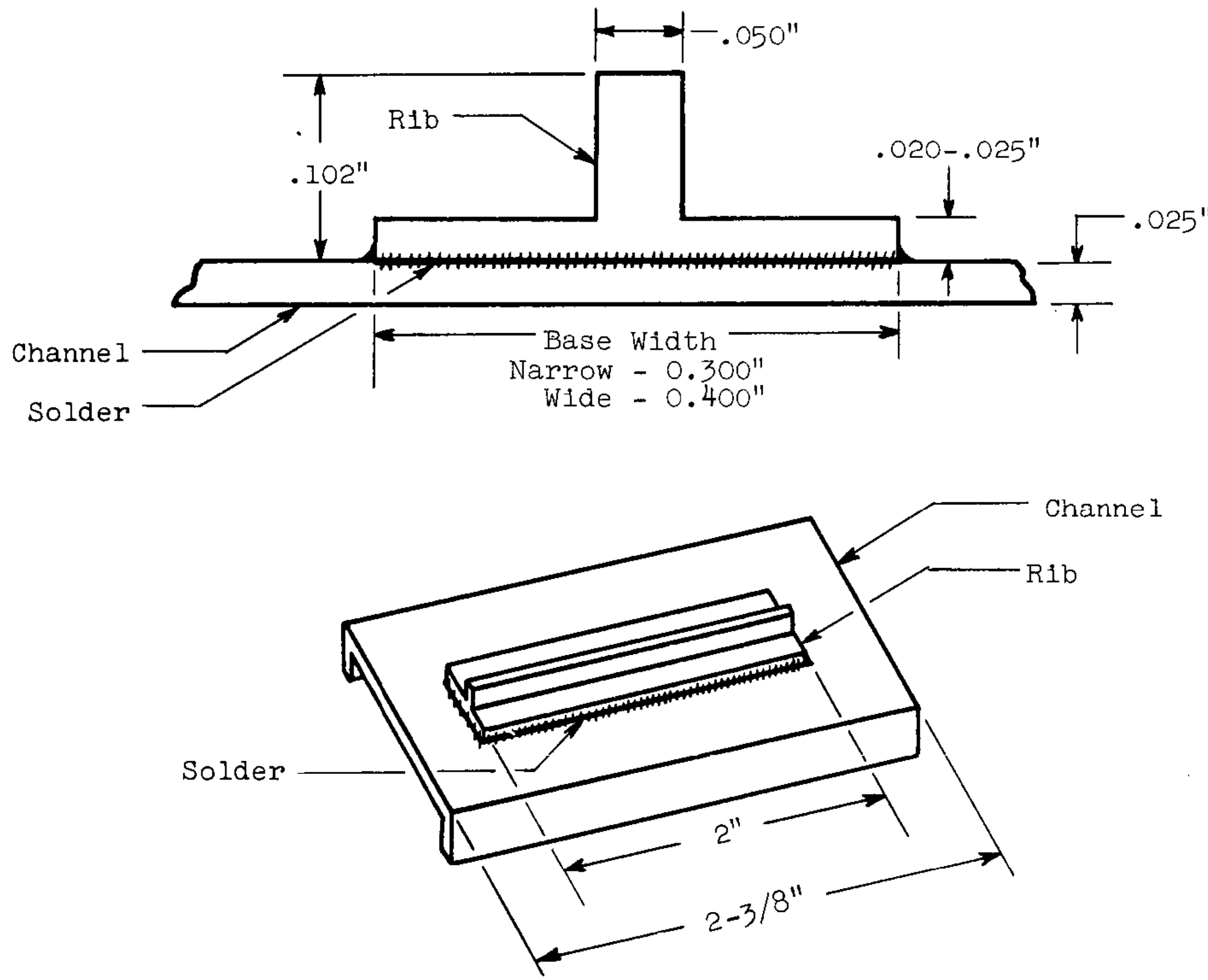


FIGURE 4

MACHINED RIB-CHANNEL CONFIGURATION

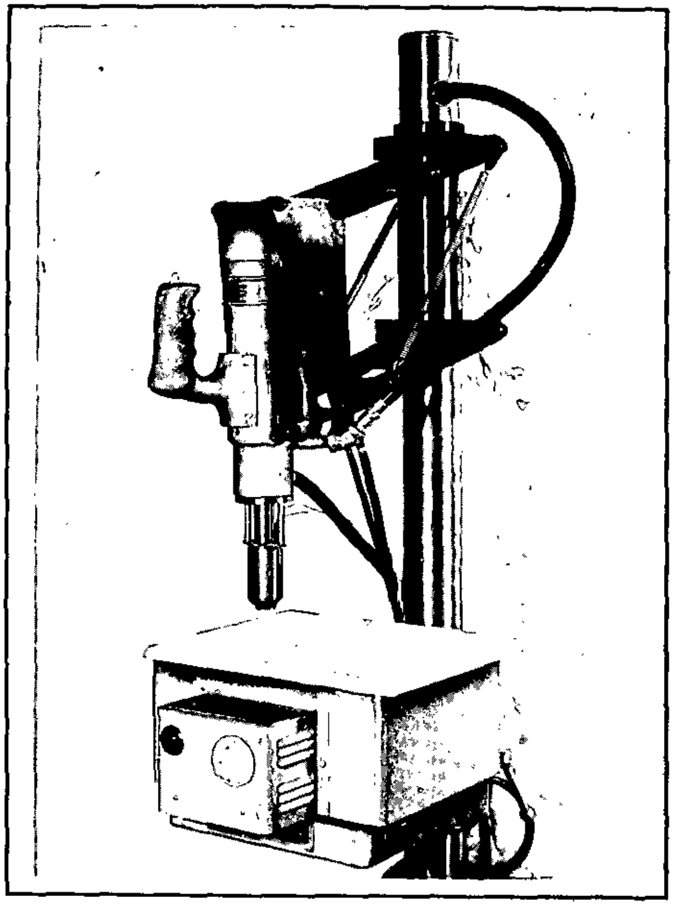


FIGURE 5

STANDARD SONOBOND
ULTRASONIC SOLDERING HEAD
AND HEATING PLATEN

15/16" Diameter Tip

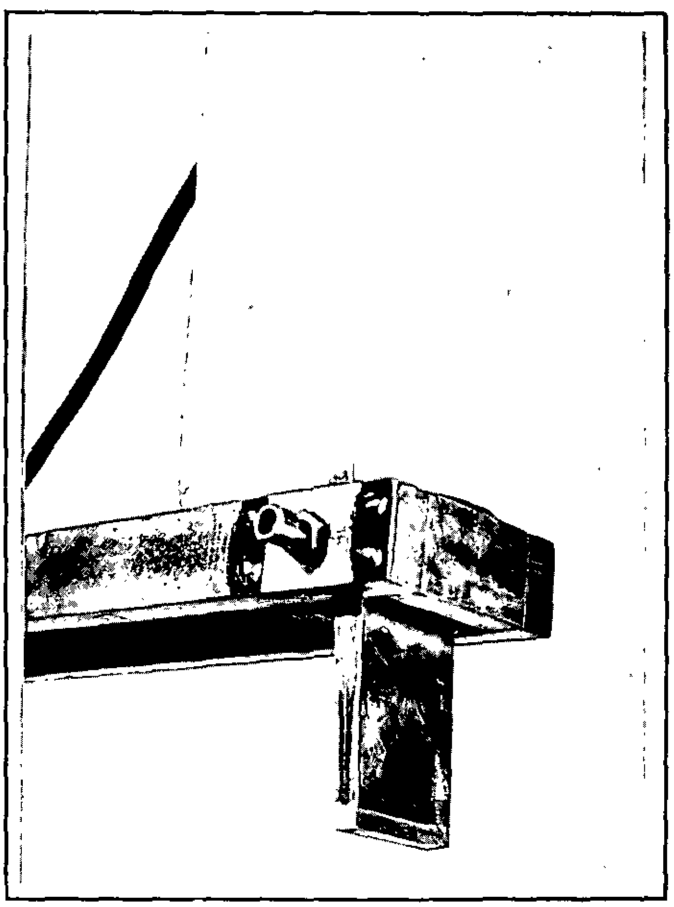
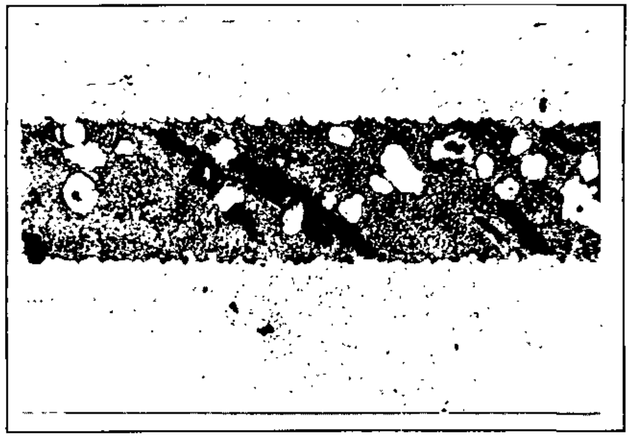


FIGURE 6

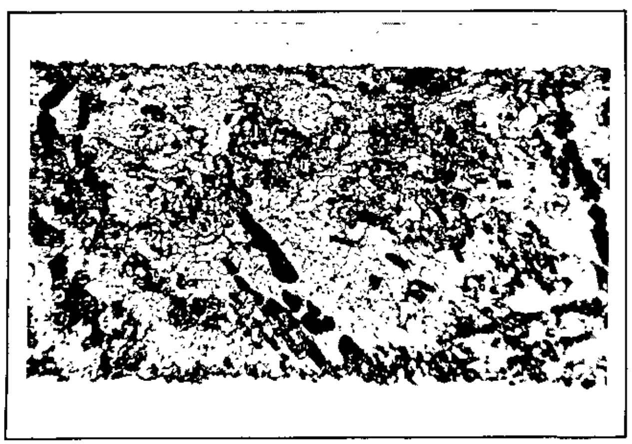
RIBBON-TYPE
ULTRASONIC SOLDERING UNIT

1/4" x 1-1/2" Rectangular Face



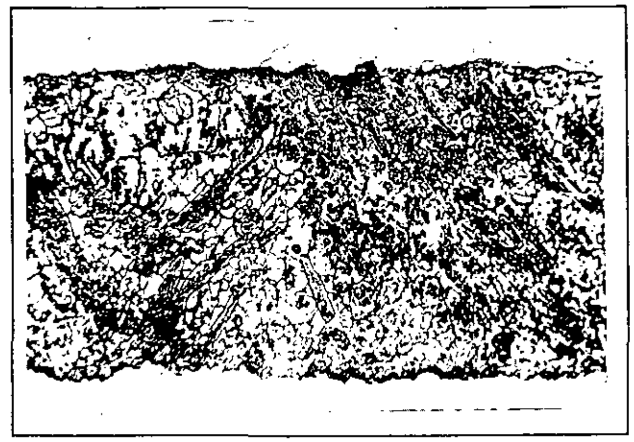
Before Exposure

After 182 hours



After 422 hours

After 902 hours

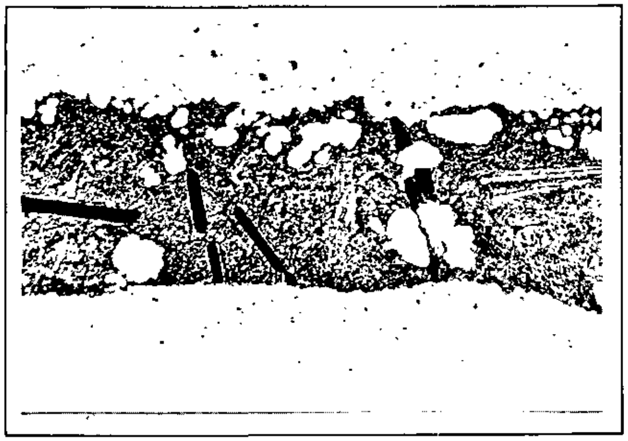


After 3638 hours

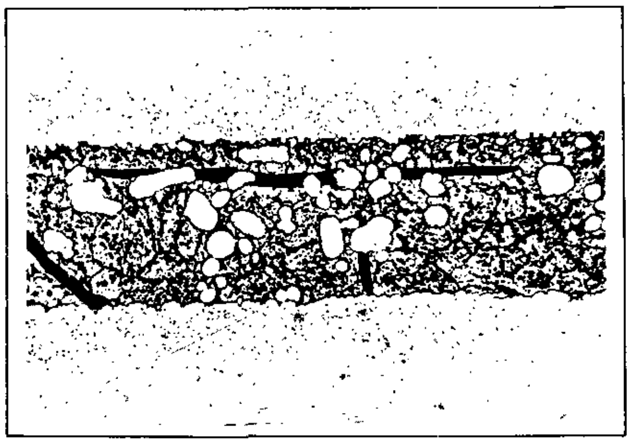
FIGURE 7

CROSS SECTIONS OF LAP JOINTS ULTRASONICALLY SOLDERED WITH 64% TIN-32% ZINC-4% ALUMINUM (SOLDER ALLOY A-1) AND EXPOSED TO 95°C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER

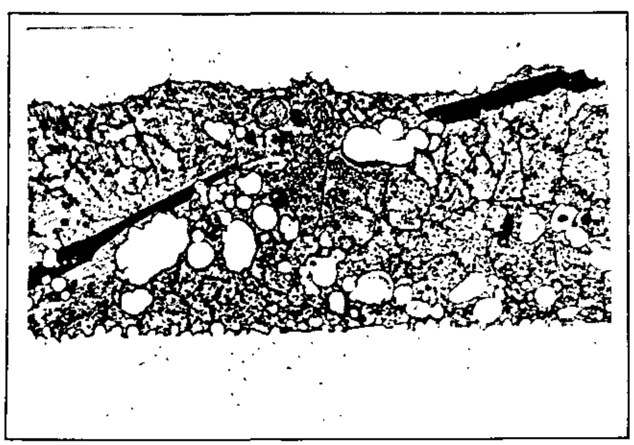
(Nital etch, 400X)



Before Exposure



After 182 hours



After 422 hours

After 902 hours

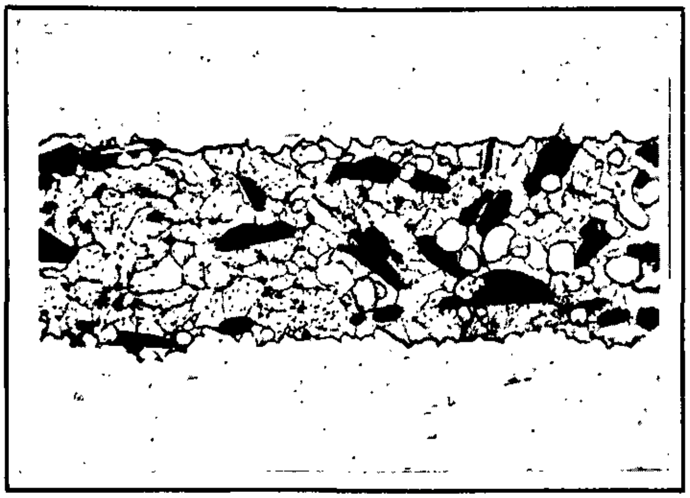
After 3638 hours

FIGURE 8

CROSS SECTIONS OF LAP JOINTS ULTRASONICALLY SOLDERED WITH 82% TIN-14% ZINC-4% ALUMINUM (SOLDER ALLOY A-6) AND EXPOSED TO 95°C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER

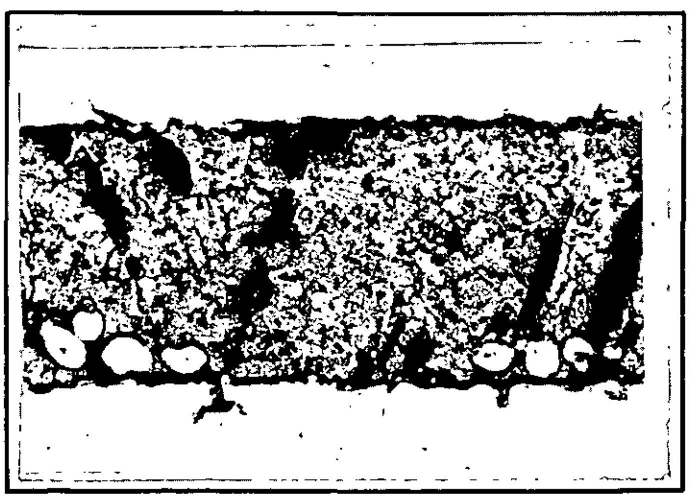
(Nital etch, 400X)

Before Exposure



After 182 hours

After 422 hours



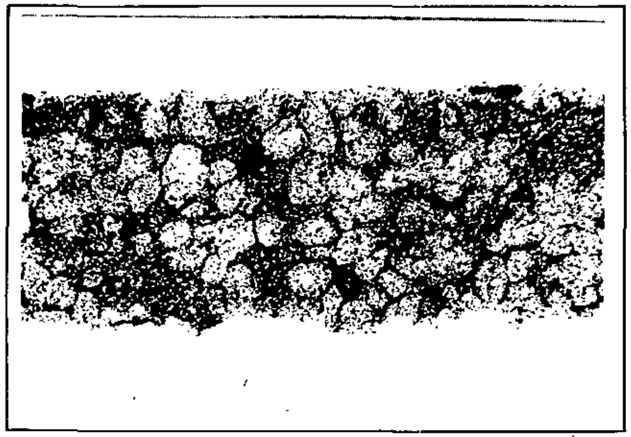
After 902 hours

After 3638 hours

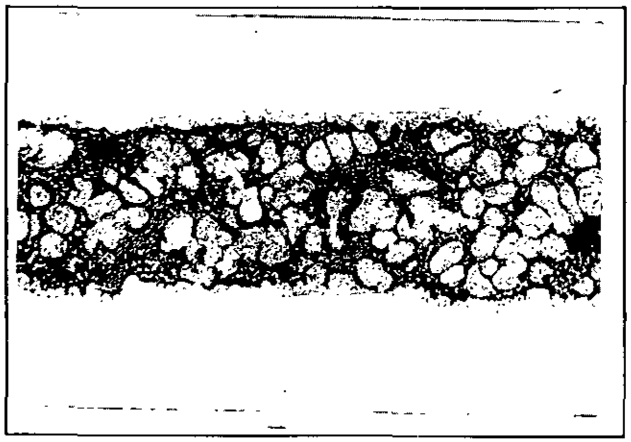
FIGURE 9

CROSS SECTIONS OF LAP JOINTS ULTRASONICALLY SOLDERED WITH 73% TIN-23% ZINC-4% ALUMINUM (SOLDER ALLOY B-1) AND EXPOSED TO 95°C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER

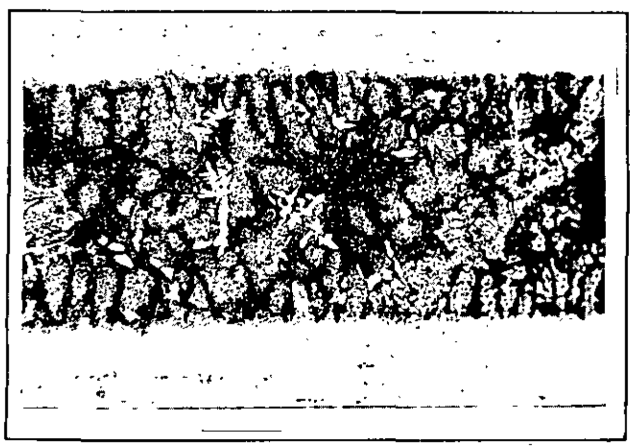
(Nital etch, 400X)



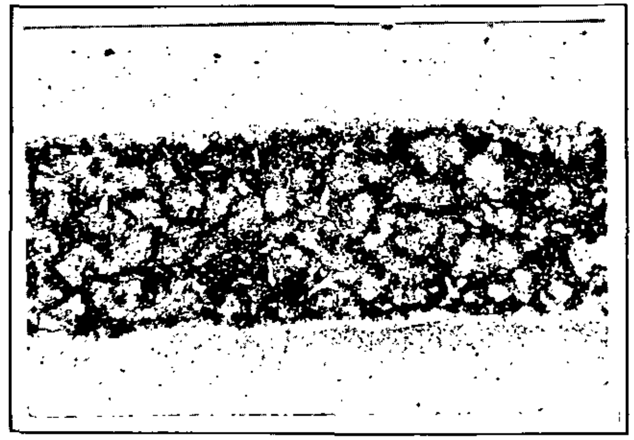
Before Exposure



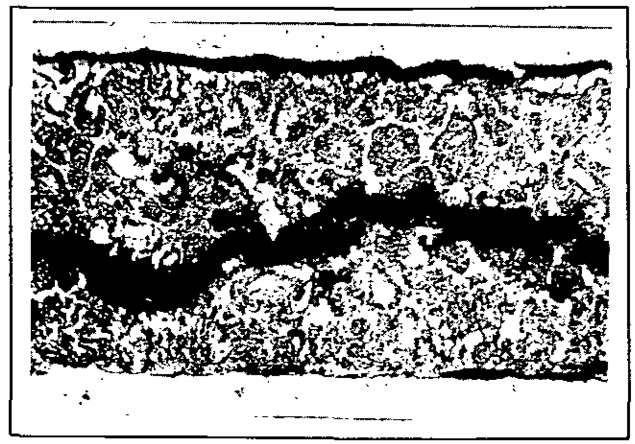
After 182 hours



After 422 hours



After 902 hours

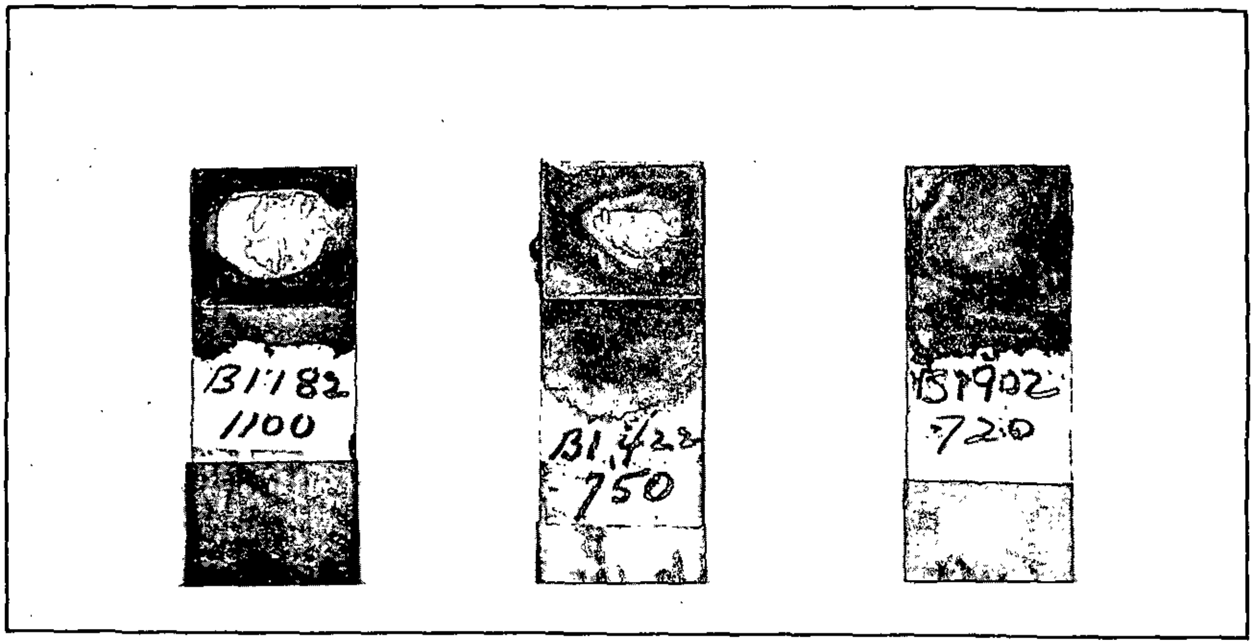


After 3638 hours

FIGURE 10

CROSS SECTIONS OF LAP JOINTS ULTRASONICALLY SOLDERED WITH 95% ZINC-5% ALUMINUM-SILICON (SOLDER ALLOY C-1) AND EXPOSED TO 95° C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER

(Nital etch, 400X)



After 182 hours of exposure | After 422 hours of exposure | After 902 hours of exposure

FIGURE 11

FRACTURED LAP SPECIMENS PREPARED WITH 73% TIN-23% ZINC-4% ALUMINUM (SOLDER ALLOY B-1) AFTER EXPOSURE IN 95°C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER

Note progressive decrease in unaffected area.

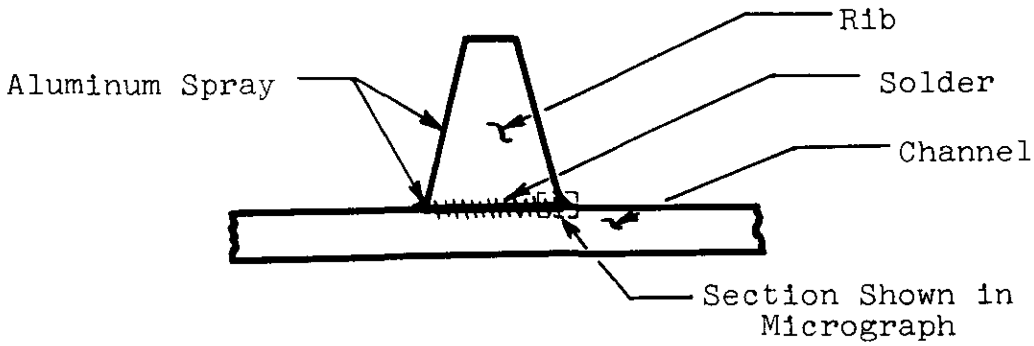


FIGURE 12

CROSS SECTION OF FILLET AREA OF RIB-CHANNEL ASSEMBLY
ULTRASONICALLY SOLDERED WITH 85% TIN-15% ZINC
AND ALUMINUM SPRAYED FOR PROTECTION
AFTER 4000 HOURS EXPOSURE IN 95°C, LOW-CONDUCTIVITY, DISTILLED WATER
AT BATTELLE MEMORIAL INSTITUTE
(0.5% HF etch, 300X)

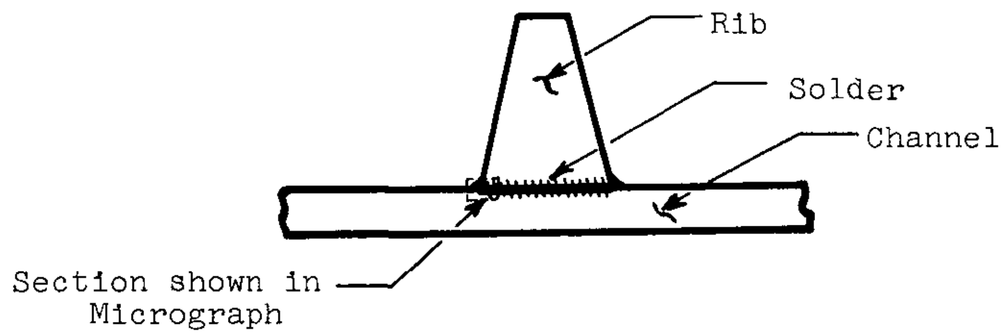
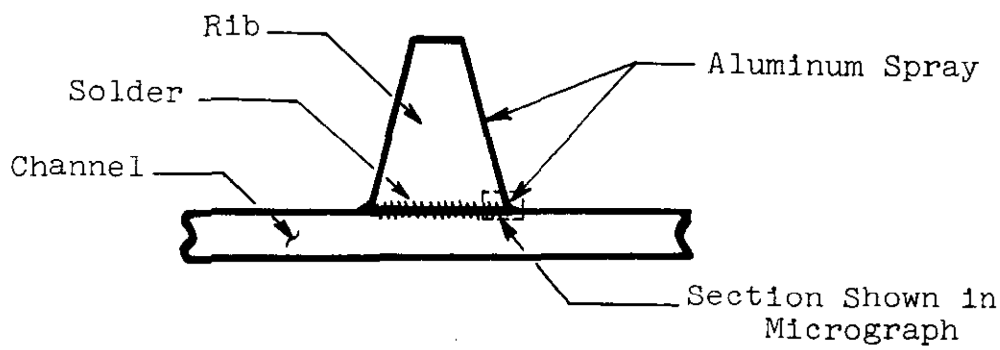


FIGURE 13

CROSS SECTION OF FILLET AREA OF RIB-CHANNEL ASSEMBLY
ULTRASONICALLY SOLDERED WITH 99% TIN-1% MAGNESIUM
AFTER 4000 HOURS EXPOSURE IN 95°C, LOW-CONDUCTIVITY, DISTILLED WATER
AT BATTELLE MEMORIAL INSTITUTE
(0.5% HF etch, 350X)



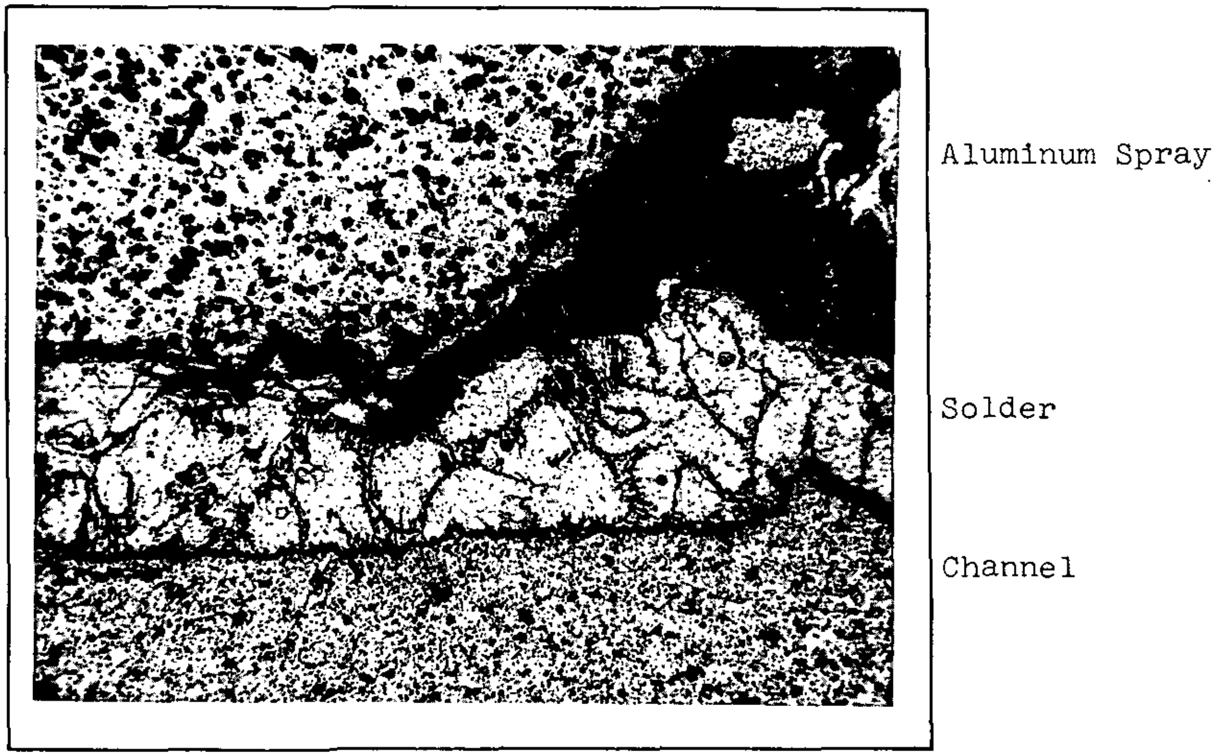


FIGURE 14

CROSS SECTION OF FILLET AREA OF RIB-CHANNEL ASSEMBLY
ULTRASONICALLY SOLDERED WITH 99% TIN-1% MAGNESIUM
AND ALUMINUM SPRAYED FOR PROTECTION
AFTER 4000 HOURS EXPOSURE IN 95°C, LOW-CONDUCTIVITY, DISTILLED WATER
AT BATTELLE MEMORIAL INSTITUTE
(0.5% HF etch, 350X)

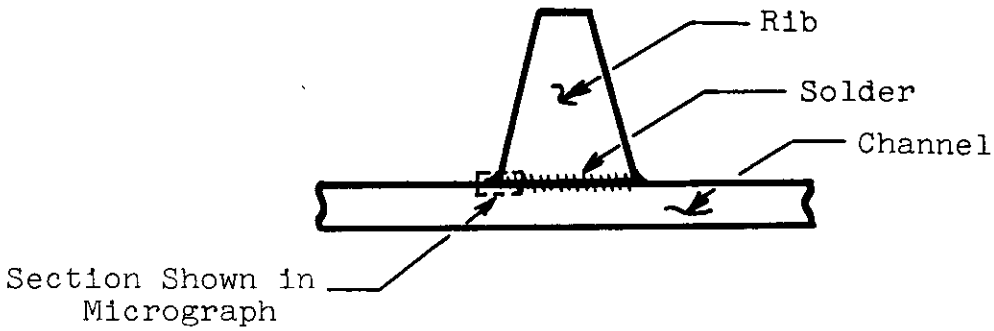


FIGURE 15

CROSS SECTION OF FILLET AREA OF RIB-CHANNEL ASSEMBLY
ULTRASONICALLY SOLDERED WITH 76% TIN-20% ZINC-4% ALUMINUM
AND AGED AT ROOM TEMPERATURE FOR 84 DAYS
(0.5% HF + 2% Nital etch, 250X)

TABLE I

RESULTS OF CORROSION TESTS ON BULK SOLDERS AT SAVANNAH RIVER LABORATORY

Sample Number	Solder Composition	Corrosion Rate (Mg/cm^2/hr)	Test Hours	Appearance
AP-19	85% Sn-15% Zn	0.005	2415	Little or no intergranular attack
AP-20	83% Sn-15% Zn-2% Al	0.05	404	Marked intergranular attack; cracked in several places
AP-21	100% Sn	0.0002	2415	Little or no intergranular attack
AP-22	80% Zn-20% Sn	0.006	2415	Little or no intergranular attack
AP-23	99% Sn-1% Mg	0.42	44	Severe intergranular attack; cracked
AP-24	99.7% Sn-0.3% Mg	0.01	44	Moderate intergranular attack; cracked
AP-25	43% Sn-55% Zn-2% Al	0.007	1387	Slight intergranular attack; cracked in several places
AP-26	95% Zn-5% Al	0.02	683	Marked intergranular attack; cracked in several places

TABLE II

RESULTS OF CORROSION TESTS AT SAVANNAH RIVER LABORATORY ON RIB SPECIMENS SOLDERED WITH 100% TIN

Rib Sample	Spray Coating	Soldering Control	Time to Failure (Hours)	Comments
AP-1	None	Nominal	363	
AP-2	None	Close	506	
AP-3	None	Close	1,027	
AP-13	Aluminum	Nominal	1,919	
AP-15	Aluminum	Close	2,202+	Test stopped; spray and rib loose at one end
AP-16	Aluminum	Close	2,202+	Test stopped; spray loose at one end
AP-14	Zinc	Nominal	139	
AP-17	Zinc	Close	139	
AP-18	Zinc	Close	139	

TABLE III

RESULTS OF CORROSION TESTS AT SAVANNAH RIVER LABORATORY ON RIB SPECIMENS SOLDERED WITH 95% ZINC-5% ALUMINUM

Rib Sample	Spray Coating	Soldering Control	Time to Failure (Hours)	Comments
AP-29	None	Nominal	95	
AP-30	None	Nominal	95	
AP-42	None	Close	114	Extensive fillet on specimens
AP-43	None	Close	159	Extensive fillet on specimens
AP-44	None	Close	159	Extensive fillet on specimens
AP-45	None	Close	141	Extensive fillet on specimens
AP-46	None	Close	114	Extensive fillet on specimens
AP-65	None	Close	163	
AP-66	None	Close	94	
AP-67	None	Close	94	
AP-68	None	Close	94	
AP-69	None	Close	94	
AP-70	None	Close	94	
AP-71	None	Close	94	
AP-72	None	Close	163	
AP-73	None	Close	94	
AP-63	Aluminum	Close	1172	Aluminum-sprayed by M & C*
AP-64	Aluminum	Close	656	Aluminum-sprayed by M & C*

* Metals and Controls Corporation, Attleboro, Mass.

TABLE IV

RESULTS OF CORROSION TESTS AT SAVANNAH RIVER LABORATORY ON RIB SPECIMENS SOLDERED WITH 95% ZINC-5% ALUMINUM-SILICON

Rib Sample	Spray Coating	Soldering Control	Time to Failure (Hours)	Comments
AP-47	None	Close	114	Extensive fillet on specimens
AP-48	None	Close	159	Extensive fillet on specimens
AP-49	None	Close	114	Extensive fillet on specimens
AP-50	None	Close	159	Extensive fillet on specimens
AP-51	None	Close	159	Extensive fillet on specimens
AP-52	None	Close	114	
AP-53	None	Close	159	
AP-54	None	Close	270	
AP-55	None	Close	270	
AP-56	None	Close	270	
AP-57	None	Close	270	
AP-58	None	Close	114	
AP-59	None	Close	159	

TABLE V

RESULTS OF CORROSION TESTS ON RIB SPECIMENS SOLDERED WITH 85% TIN-15% ZINC

A. Savannah River Tests

Rib Sample	Spray Coating	Time to Failure (Hours)	Comments
AP-4	None	506	
AP-5	None	457	
AP-6	None	651	
AP-7	Aluminum	2,832+	Test stopped; rib loose at one end, spray started to loosen at edges
AP-9	Aluminum	2,832+	Test stopped; rib loose at one end, spray loose at other end
AP-10	Aluminum	2,832+	Test stopped; spray loose at one end
AP-8	Zinc	651	
AP-11	Zinc	744	
AP-12	Zinc	316	

B. Battelle Tests

Rib Sample	Coating on Ribs	Coating on Ends	Time to Failure (Hours)	Comments
1-A	None	None	4000+	Test stopped; specimen in excellent condition
1-B	Aluminum	None	4000+	Test stopped; specimen in excellent condition
1-C	Aluminum	Aluminum	4000+	Test stopped; specimen in excellent condition
1-D	Zinc	None	144	
1-E	Zinc	Zinc	144	

TABLE VI

RESULTS OF CORROSION TESTS ON RIB SPECIMENS SOLDERED WITH 99% TIN-1% MAGNESIUM

A. Savannah River Tests

Rib Sample	Spray Coating	Time to Failure (Hours)	Comments
AP-27	None	747	
AP-28	None	772	
AP-60	Aluminum (M&C)	1600+	Still in test
AP-61	Aluminum (M&C)	1600+	Still in test
AP-62	Aluminum (M&C)	1600+	Still in test

B. Battelle Tests

Rib Sample	Coating on Ribs	Coating on Ends	Time to Failure (Hours)	Comments
2-A	None	None	4000+	Test stopped; specimen in excellent condition
2-B	Aluminum	None	4000+	Test stopped; specimen in excellent condition
2-C	Aluminum	Aluminum	4000+	Test stopped; specimen in excellent condition
2-D	Zinc	None	144	
2-E	Zinc	Zinc	144	

TABLE VII

RESULTS OF CORROSION TESTS AT SAVANNAH RIVER LABORATORY
ON FOLDED RIB SPECIMENS SOLDERED WITH 95% ZINC-5% ALUMINUM-SILICON

Reagent Grade			High Purity Grade		
Rib Sample	Coating	Time to Failure (Hours)	Rib Sample	Coating	Time to Failure (Hours)
AP-74	None	646			
AP-75	None	295			
AP-76	None	600+			
AP-77	None	600+			
AP-78	None	229			
AP-121	None	295			
AP-104	Greased	500+	AP-101	Greased	500+
AP-105	Greased	500+	AP-102	Greased	500+
AP-106	Greased	500+	AP-103	Greased	500+
AP-115	Al Spray	573	AP-113	Al Spray	500+
AP-116	Al Spray	573	AP-114	Al Spray	405
AP-95	Al Spray, greased	500+	AP-93	Al Spray, greased	500+
AP-96	Al Spray, greased	500+	AP-94	Al Spray, greased	500+
AP-87	Al Spray, burnished	229	AP-85	Al Spray, greased	525
AP-88	Al Spray, burnished	646	AP-86	Al Spray, burnished	295

TABLE VIII

RESULTS OF CORROSION TESTS AT SAVANNAH RIVER LABORATORY ON FOLDED RIB SPECIMENS SOLDERED WITH 73% TIN-23% ZINC-4% ALUMINUM

Reagent Grade			High Purity Grade		
Rib Sample	Coating	Time to Failure (Hours)	Rib Sample	Coating	Time to Failure (Hours)
AP-82	None	229	AP-79	None	229
AP-83	None	229	AP-80	None	229
AP-84	None	162	AP-81	None	229
AP-110	Greased	258	AP-107	Greased	358
AP-111	Greased	479	AP-108	Greased	479
AP-112	Greased	358	AP-109	Greased	479
AP-117	Al Spray	156	AP-119	Al Spray	156
AP-118	Al Spray	89	AP-120	Al Spray	229
AP-99	Al Spray, greased	358	AP-97	Al Spray, greased	479
AP-100	Al Spray, greased	358	AP-98	Al Spray, greased	479
AP-90	Al Spray, burnished	229	AP-89	Al Spray, burnished	229
AP-91	Al Spray, burnished	229	AP-90	Al Spray, burnished	229

TABLE IX

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder A-1: 64% Sn-32% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
143	0.300	None	None	568
144	0.300	None	None	164
145	0.300	None	None	261
308	0.400	None	None	260
309	0.400	None	None	260
310	0.400	None	None	260
140	0.300	Aluminum	None	837
141	0.300	Aluminum	None	837
142	0.300	Aluminum	None	837
134	0.300	Aluminum	Burnished	837
135	0.300	Aluminum	Burnished	837
136	0.300	Aluminum	Burnished	1534
131	0.300	Aluminum	DC-7 Silicone	408
132	0.300	Aluminum	DC-7 Silicone	408
133	0.300	Aluminum	DC-7 Silicone	408
137	0.300	Aluminum	Metco SiAl	1752
138	0.300	Aluminum	Metco SiAl	332
139	0.300	Aluminum	Metco SiAl	332
128	0.300	Aluminum	du Pont "Butanol"	237
129	0.300	Aluminum	du Pont "Butanol"	549
130	0.300	Aluminum	du Pont "Butanol"	549

TABLE X

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder A-2: 67% Sn-29% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
161	0.300	None	None	261
162	0.300	None	None	261
163	0.300	None	None	568
311	0.400	None	None	260
312	0.400	None	None	260
313	0.400	None	None	408
146	0.300	Aluminum	None	1240
147	0.300	Aluminum	None	1240
148	0.300	Aluminum	None	1240
149	0.300	Aluminum	Burnished	837
150	0.300	Aluminum	Burnished	431
151	0.300	Aluminum	Burnished	1240
152	0.300	Aluminum	DC-7 Silicone	408
153	0.300	Aluminum	DC-7 Silicone	408
154	0.300	Aluminum	DC-7 Silicone	408
158	0.300	Aluminum	Metco SiAl	1240
159	0.300	Aluminum	Metco SiAl	332
160	0.300	Aluminum	Metco SiAl	332
155	0.300	Aluminum	du Pont "Butanol"	984
156	0.300	Aluminum	du Pont "Butanol"	237
157	0.300	Aluminum	du Pont "Butanol"	549

TABLE XI

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder A-3: 70% Sn-26% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
179	0.300	None	None	568
180	0.300	None	None	261
181	0.300	None	None	734
314	0.400	None	None	260
315	0.400	None	None	260
316	0.400	None	None	260
167	0.300	Aluminum	None	1534
168	0.300	Aluminum	None	1534
169	0.300	Aluminum	None	837
164	0.300	Aluminum	Burnished	837
165	0.300	Aluminum	Burnished	837
166	0.300	Aluminum	Burnished	1240
170	0.300	Aluminum	DC-7 Silicone	408
171	0.300	Aluminum	DC-7 Silicone	408
172	0.300	Aluminum	DC-7 Silicone	408
173	0.300	Aluminum	Metco SiAl	1475
174	0.300	Aluminum	Metco SiAl	1240
175	0.300	Aluminum	Metco SiAl	1475
176	0.300	Aluminum	du Pont "Butanol"	237
177	0.300	Aluminum	du Pont "Butanol"	549
178	0.300	Aluminum	du Pont "Butanol"	549

TABLE XII

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder A-4: 76% Sn-20% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
197	0.300	None	None	568
198	0.300	None	None	1140
199	0.300	None	None	1140
317	0.400	None	None	260
318	0.400	None	None	260
319	0.400	None	None	260
185	0.300	Aluminum	None	1534
186	0.300	Aluminum	None	1240
187	0.300	Aluminum	None	1866
182	0.300	Aluminum	Burnished	1240
183	0.300	Aluminum	Burnished	1240
184	0.300	Aluminum	Burnished	837
188	0.300	Aluminum	DC-7 Silicone	408
189	0.300	Aluminum	DC-7 Silicone	408
190	0.300	Aluminum	DC-7 Silicone	408
191	0.300	Aluminum	Metco SiAl	1475
192	0.300	Aluminum	Metco SiAl	1475
193	0.300	Aluminum	Metco SiAl	1240
194	0.300	Aluminum	du Pont "Butanol"	237
195	0.300	Aluminum	du Pont "Butanol"	549
196	0.300	Aluminum	du Pont "Butanol"	549

TABLE XIII

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder A-5: 79% Sn-17% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
215	0.300	None	None	1140
216	0.300	None	None	1543
217	0.300	None	None	1140
320	0.400	None	None	260
321	0.400	None	None	260
322	0.400	None	None	240
209	0.300	Aluminum	None	1866
210	0.300	Aluminum	None	1240
211	0.300	Aluminum	None	1866
212	0.300	Aluminum	Burnished	1240
213	0.300	Aluminum	Burnished	1534
214	0.300	Aluminum	Burnished	837
206	0.300	Aluminum	DC-7 Silicone	408
207	0.300	Aluminum	DC-7 Silicone	408
208	0.300	Aluminum	DC-7 Silicone	408
203	0.300	Aluminum	Metco SiAl	1240
204	0.300	Aluminum	Metco SiAl	1608
205	0.300	Aluminum	Metco SiAl	1475
200	0.300	Aluminum	du Pont "Butanol"	1512
201	0.300	Aluminum	du Pont "Butanol"	549
202	0.300	Aluminum	du Pont "Butanol"	1512

TABLE XIV

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder A-6: 82% Sn-14% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
233	0.300	None	None	568
234	0.300	None	None	1140
235	0.300	None	None	1140
323	0.400	None	None	260
324	0.400	None	None	260
325	0.400	None	None	260
218	0.300	Aluminum	None	1240
219	0.300	Aluminum	None	1240
220	0.300	Aluminum	None	1240
221	0.300	Aluminum	Burnished	644
222	0.300	Aluminum	Burnished	1240
223	0.300	Aluminum	Burnished	1240
224	0.300	Aluminum	DC-7 Silicone	600
225	0.300	Aluminum	DC-7 Silicone	408
226	0.300	Aluminum	DC-7 Silicone	600
227	0.300	Aluminum	Metco SiAl	1416
228	0.300	Aluminum	Metco SiAl	1608
229	0.300	Aluminum	Metco SiAl	1416
230	0.300	Aluminum	du Pont "Butanol"	1512
231	0.300	Aluminum	du Pont "Butanol"	984
232	0.300	Aluminum	du Pont "Butanol"	1656

TABLE XV

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder B-1: 73% Sn-23% Zn-4% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
251	0.300	None	None	568
252	0.300	None	None	1140
253	0.300	None	None	1140
326	0.400	None	None	260
327	0.400	None	None	260
328	0.400	None	None	260
239	0.300	Aluminum	None	1866
240	0.300	Aluminum	None	837
241	0.300	Aluminum	None	1534
236	0.300	Aluminum	Burnished	332
237	0.300	Aluminum	Burnished	332
238	0.300	Aluminum	Burnished	332
242	0.300	Aluminum	DC-7 Silicone	600
243	0.300	Aluminum	DC-7 Silicone	408
244	0.300	Aluminum	DC-7 Silicone	408
245	0 300	Aluminum	Metco SiAl	1240
246	0.300	Aluminum	Metco SiAl	837
247	0.300	Aluminum	Metco SiAl	1416
248	0.300	Aluminum	du Pont "Butanol"	237
249	0 300	Aluminum	du Pont "Butanol"	549
250	0.300	Aluminum	du Pont "Butanol"	984

TABLE XVI

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder B-2: 60% Sn-35% Zn-5% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
269	0.300	None	None	568
270	0.300	None	None	164
271	0.300	None	None	164
329	0.400	None	None	260
330	0.400	None	None	260
331	0.400	None	None	260
263	0.300	Aluminum	None	1240
264	0.300	Aluminum	None	263
265	0.300	Aluminum	None	431
260	0.300	Aluminum	Burnished	332
261	0.300	Aluminum	Burnished	332
262	0.300	Aluminum	Burnished	332
257	0.300	Aluminum	DC-7 Silicone	1104
258	0.300	Aluminum	DC-7 Silicone	1104
259	0.300	Aluminum	DC-7 Silicone	408
254	0.300	Aluminum	Metco SiAl	644
255	0.300	Aluminum	Metco SiAl	644
256	0.300	Aluminum	Metco SiAl	1240
266	0.300	Aluminum	du Pont "Butanol"	237
267	0.300	Aluminum	du Pont "Butanol"	237
268	0.300	Aluminum	du Pont "Butanol"	237

TABLE XVII

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder B-3: 58% Sn-36% Zn-6% Al

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
287	0.300	None	None	164
288	0.300	None	None	164
289	0.300	None	None	261
332	0.400	None	None	260
333	0.400	None	None	260
334	0.400	None	None	260
281	0.300	Aluminum	None	263
282	0.300	Aluminum	None	837
283	0.300	Aluminum	None	2178
275	0.300	Aluminum	Burnished	332
276	0.300	Aluminum	Burnished	1416
277	0.300	Aluminum	Burnished	332
278	0.300	Aluminum	DC-7 Silicone	408
279	0.300	Aluminum	DC-7 Silicone	1104
280	0.300	Aluminum	DC-7 Silicone	600
284	0.300	Aluminum	Metco SiAl	332
285	0.300	Aluminum	Metco SiAl	644
286	0.300	Aluminum	Metco SiAl	644
272	0.300	Aluminum	du Pont "Butanol"	984
273	0.300	Aluminum	du Pont "Butanol"	1320
274	0.300	Aluminum	du Pont "Butanol"	237

TABLE XVIII

RESULTS OF CORROSION TESTS ON RIB SPECIMENS AT SAVANNAH RIVER LABORATORY

Solder C-1: 95% Zn-5% AlSi

Rib Sample	Rib Base Width (inches)	Metal Spray	Coating on Metal Spray	Time to Failure (hours)
305	0.300	None	None	3552
306	0.300	None	None	399
307	0.300	None	None	734
335	0.400	None	None	1128
336	0.400	None	None	620
337	0.400	None	None	620
290	0.300	Aluminum	None	3288
291	0.300	Aluminum	None	3140
292	0.300	Aluminum	None	1866
299	0.300	Aluminum	Burnished	837
300	0.300	Aluminum	Burnished	644
301	0.300	Aluminum	Burnished	2111
293	0.300	Aluminum	DC-7 Silicone	1104
294	0.300	Aluminum	DC-7 Silicone	1104
295	0.300	Aluminum	DC-7 Silicone	1104
296	0.300	Aluminum	Metco SiAl	837
297	0.300	Aluminum	Metco SiAl	2111
298	0.300	Aluminum	Metco SiAl	1416
302	0.300	Aluminum	du Pont "Butanol"	742
303	0.300	Aluminum	du Pont "Butanol"	742
304	0.300	Aluminum	du Pont "Butanol"	549

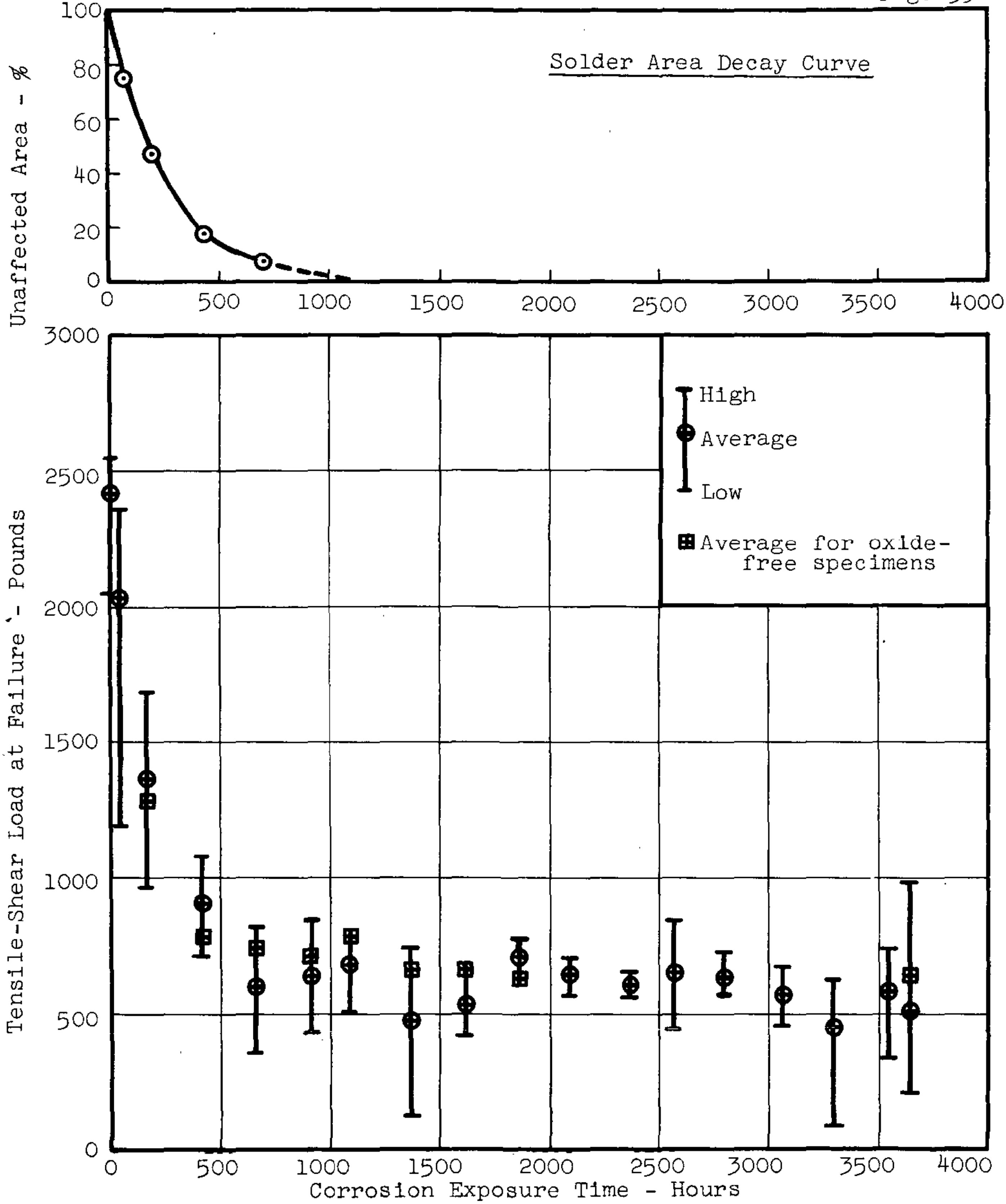


CHART 1

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY A-1
(64% TIN-32% ZINC-4% ALUMINUM)

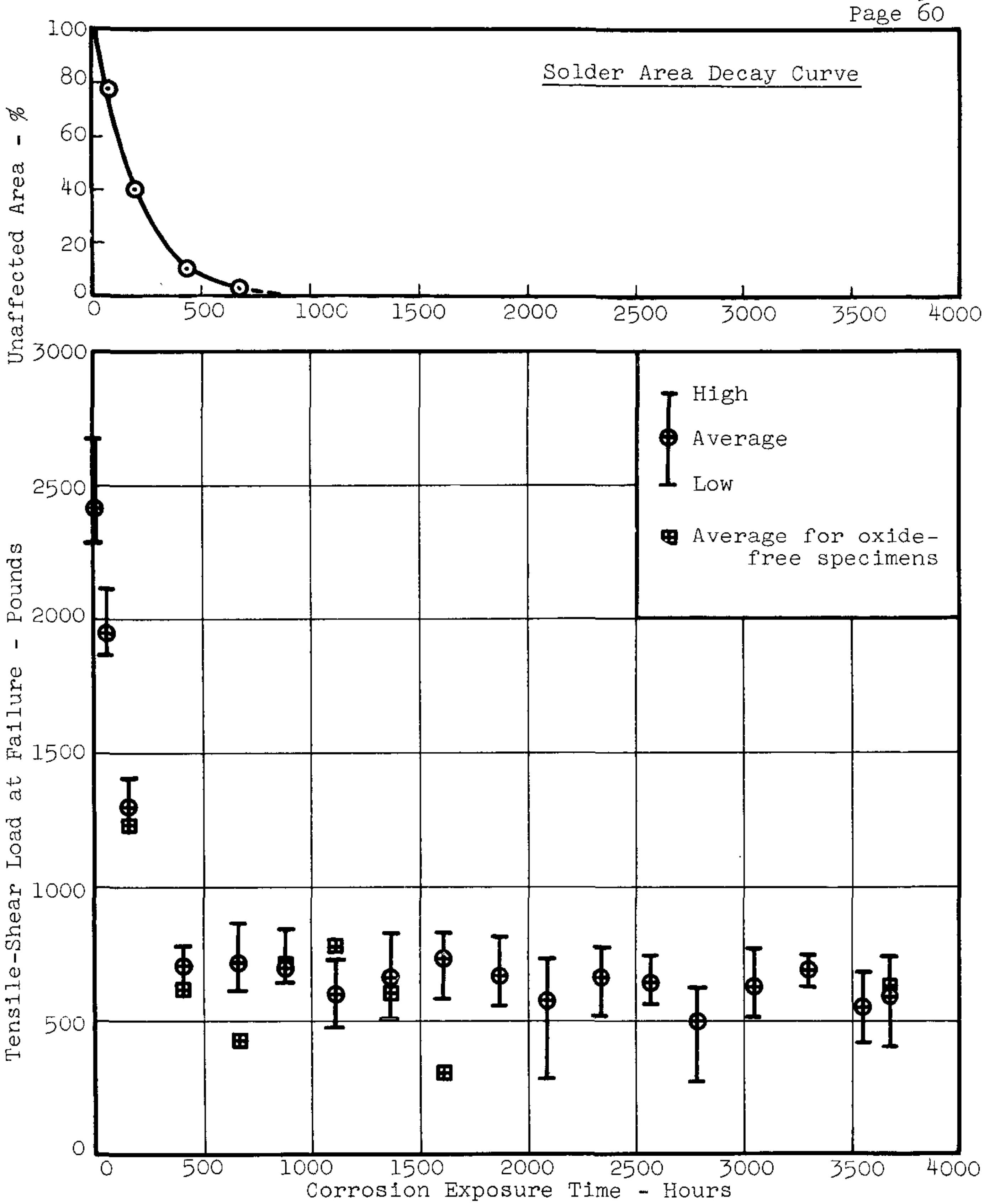


CHART 2

RESULTS OF CORROSION TESTS ON LAP SPECIMENS PREPARED WITH SOLDER ALLOY A-2
(67% TIN-29% ZINC-4% ALUMINUM)

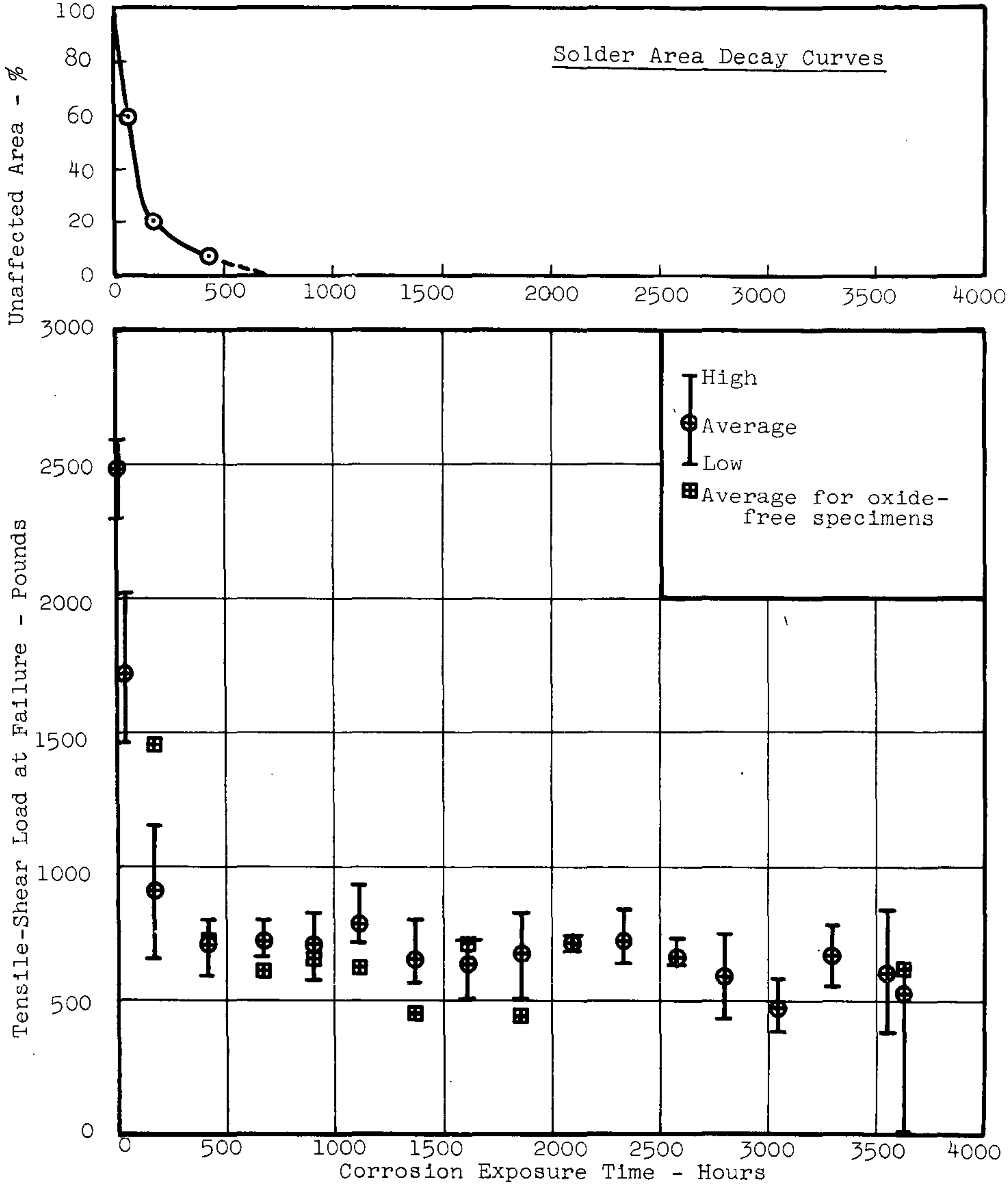


CHART 3

RESULTS OF CORROSION TESTS ON LAP SPECIMENS PREPARED WITH SOLDER ALLOY A-3 (70% TIN-26% ZINC-4% ALUMINUM)

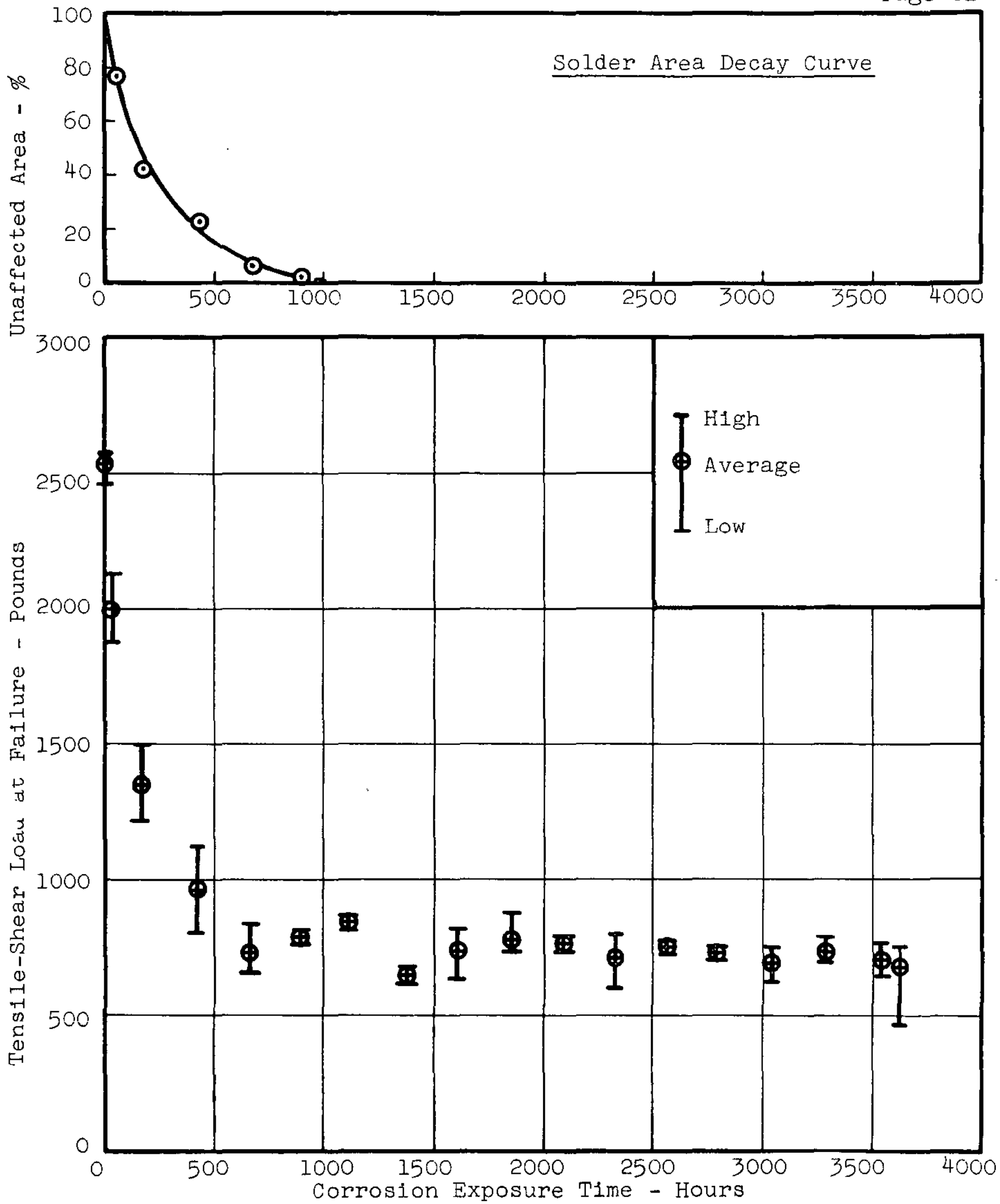


CHART 4

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY A-4
(76% TIN-20% ZINC-4% ALUMINUM)

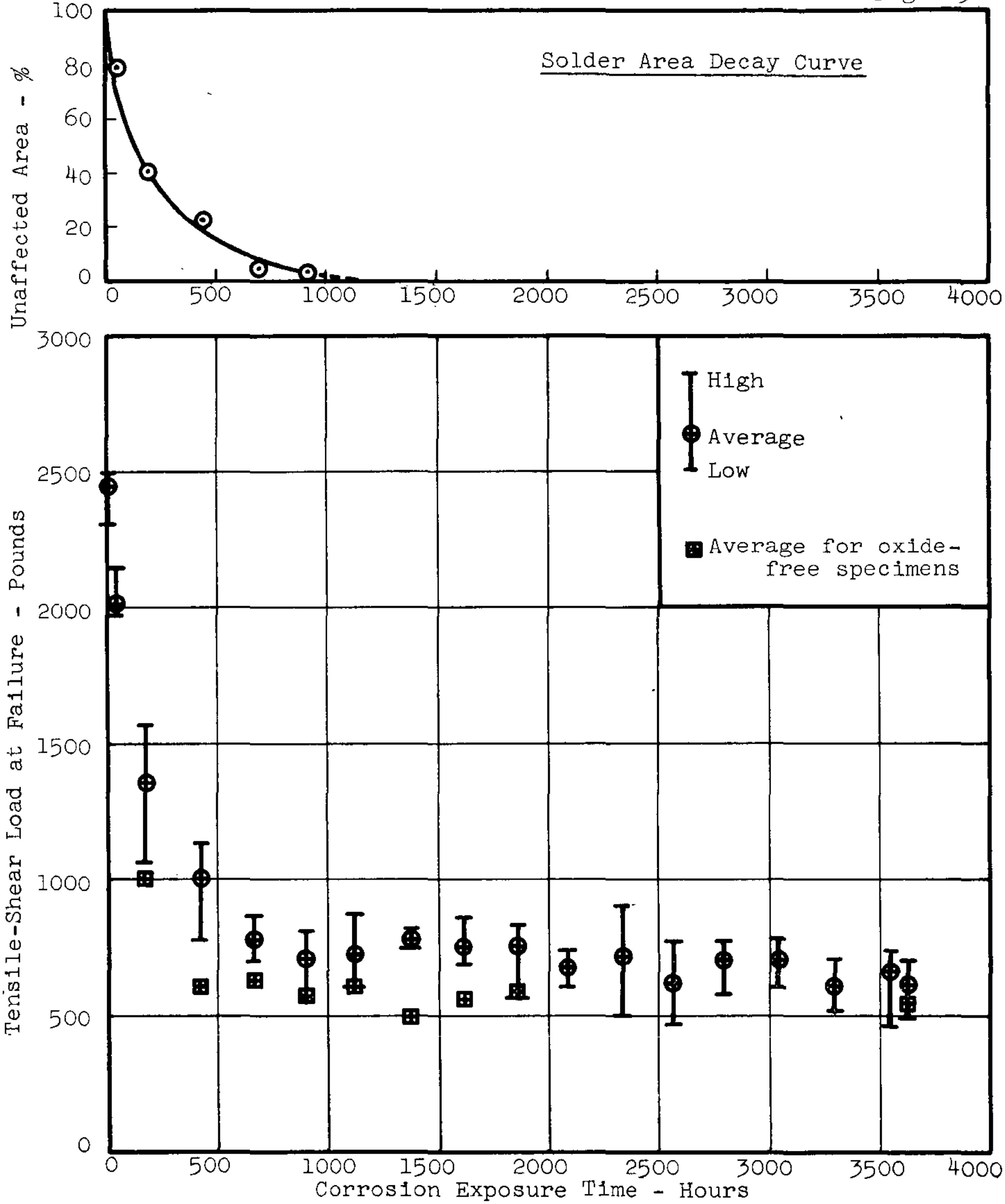


CHART 5

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY A-5
(79% TIN-17% ZINC-4% ALUMINUM)

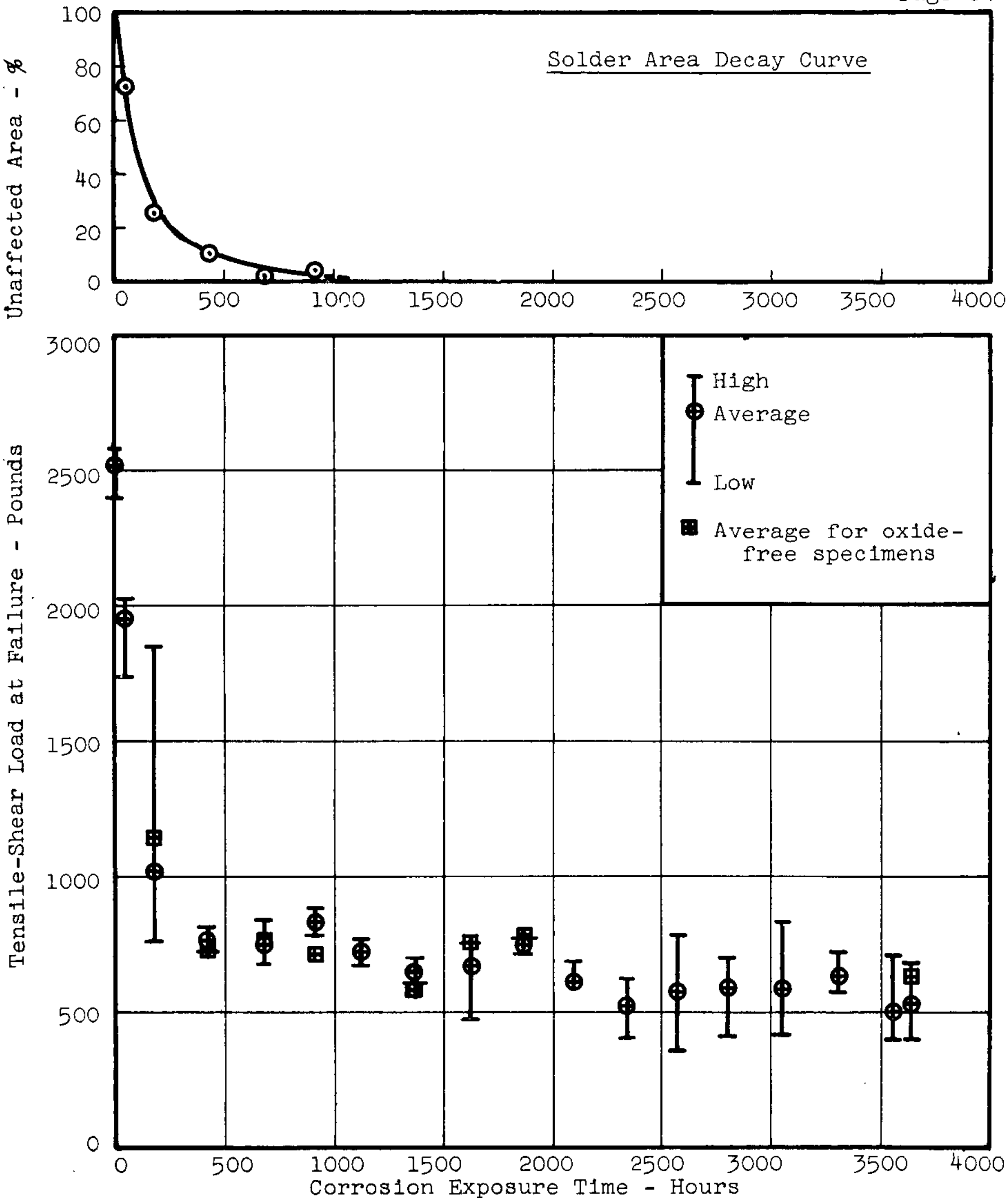


CHART 6

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY A-6
(82% TIN-14% ZINC-4% ALUMINUM)

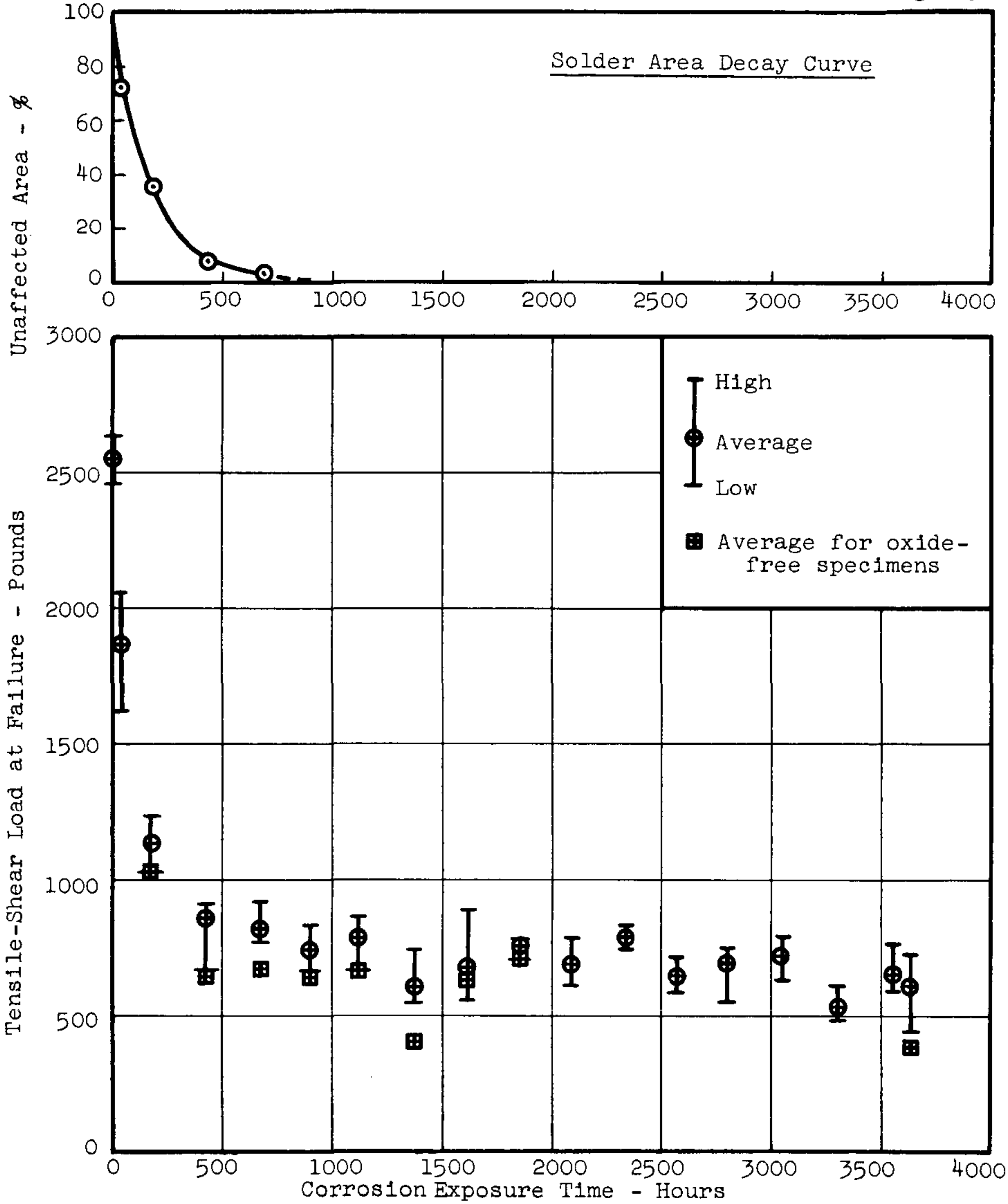


CHART 7

RESULTS OF CORROSION TESTS ON LAP SPECIMENS PREPARED WITH SOLDER ALLOY B-1 (73% TIN-23% ZINC-4% ALUMINUM)

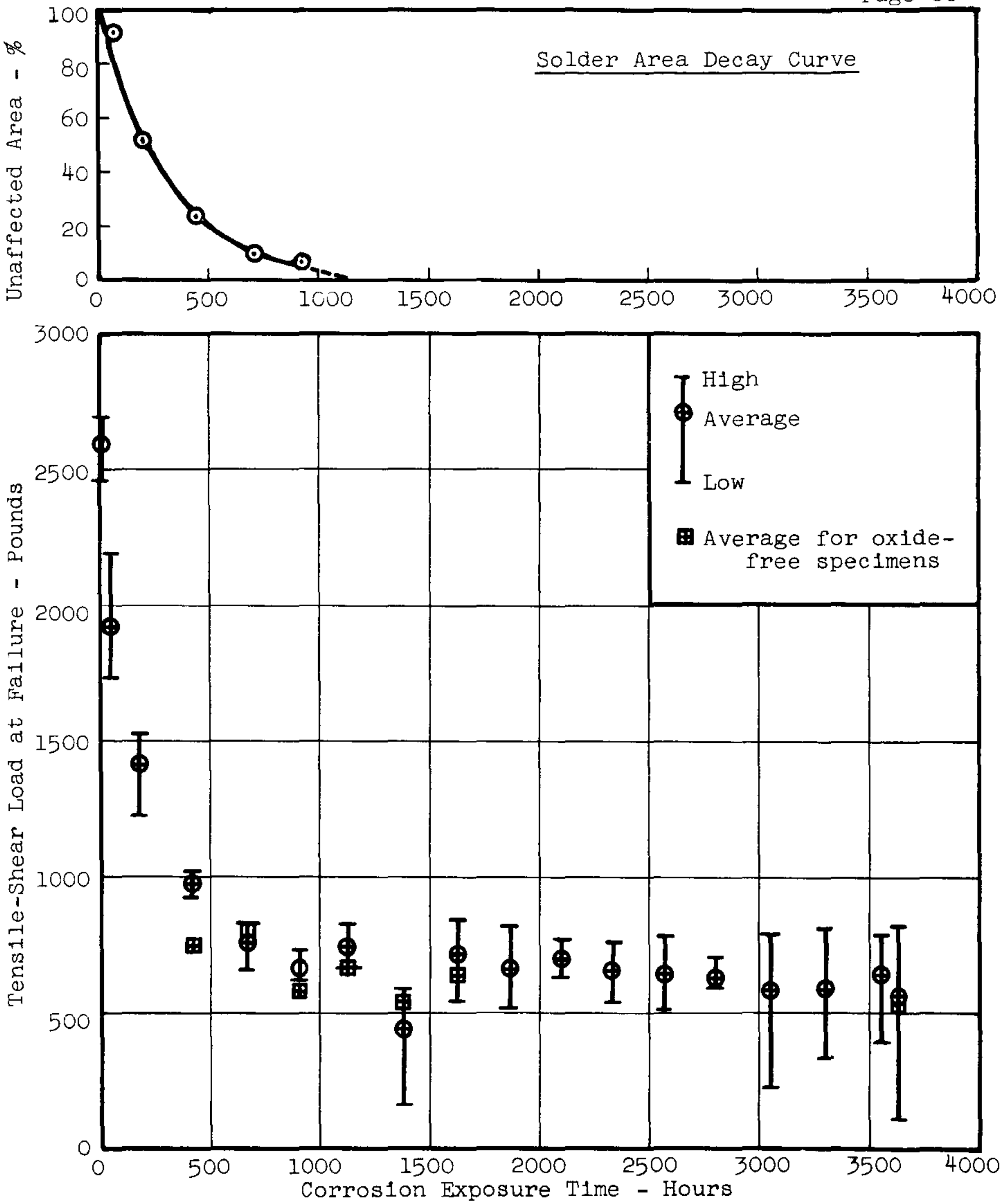


CHART 8

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY B-2
(60% TIN-35% ZINC-5% ALUMINUM)

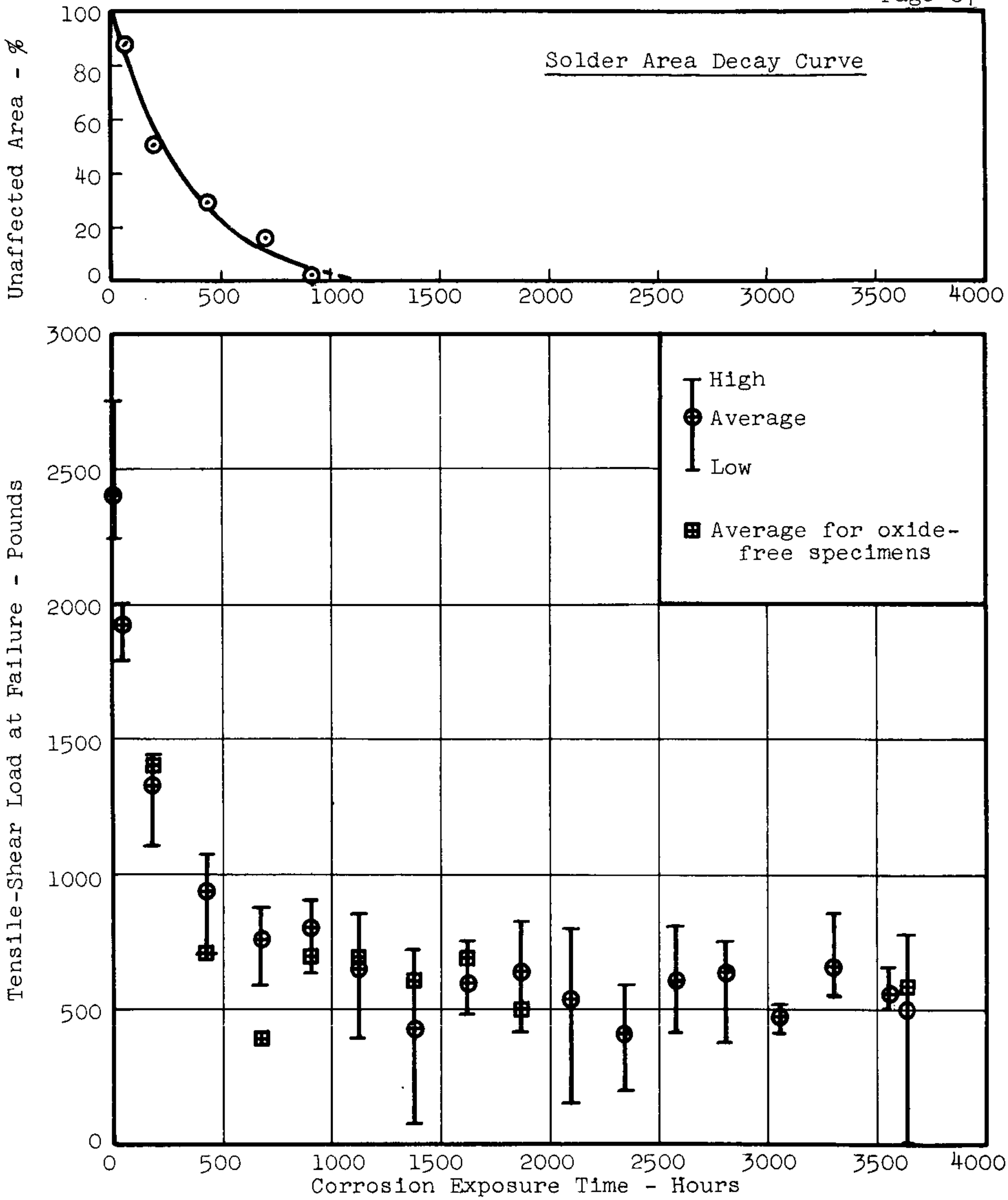


CHART 9

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY B-3
(58% TIN-36% ZINC-6% ALUMINUM)

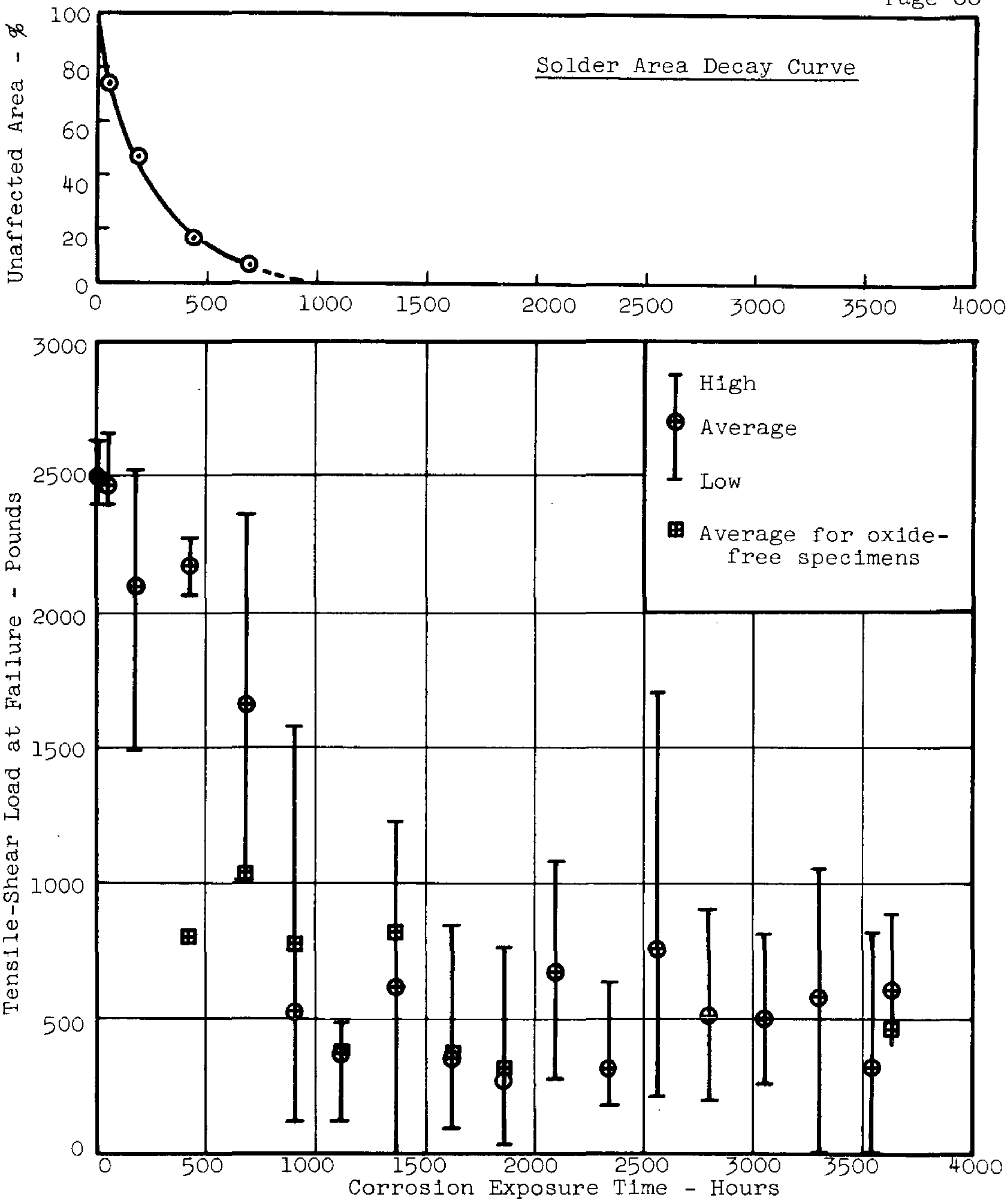


CHART 10

RESULTS OF CORROSION TESTS ON LAP SPECIMENS
PREPARED WITH SOLDER ALLOY C-1
(95% ZINC-5% ALUMINUM-SILICON)

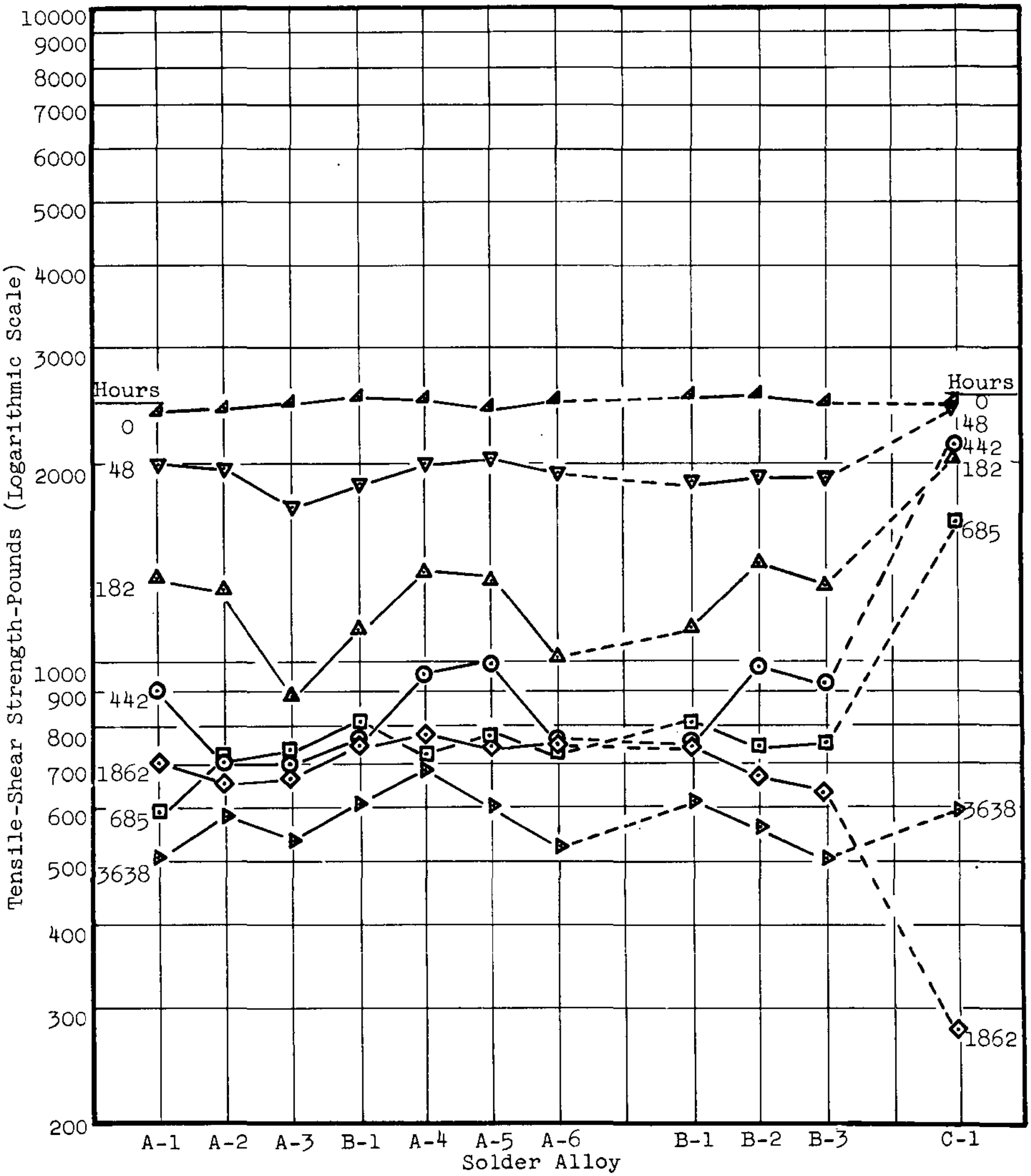


CHART 11

STRENGTH OF ULTRASONICALLY SOLDERED LAP SPECIMENS AT SELECTED CORROSION EXPOSURE TIMES

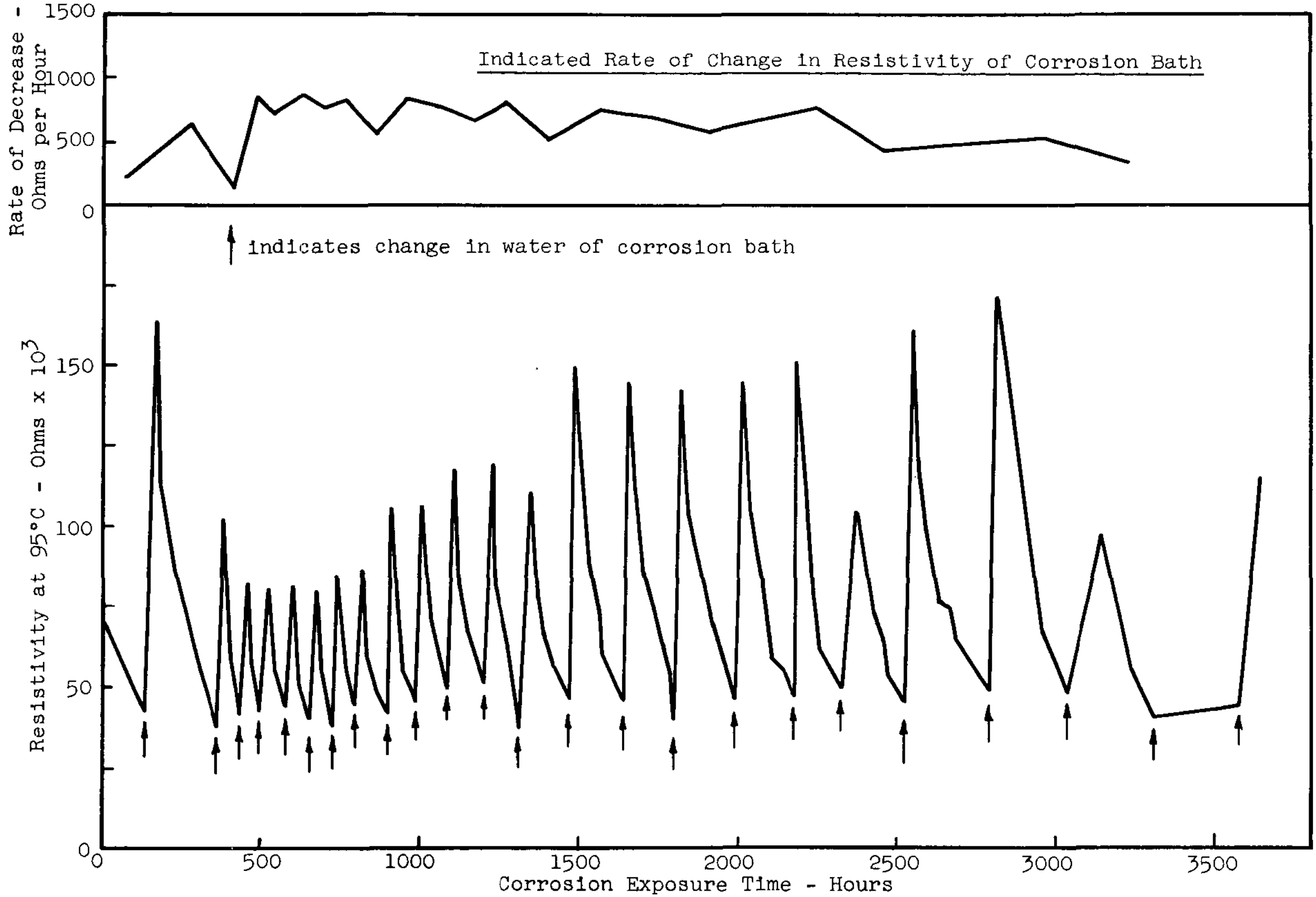


CHART 12

RESISTIVITY OF CORROSION BATH FOR SOLDER A-1

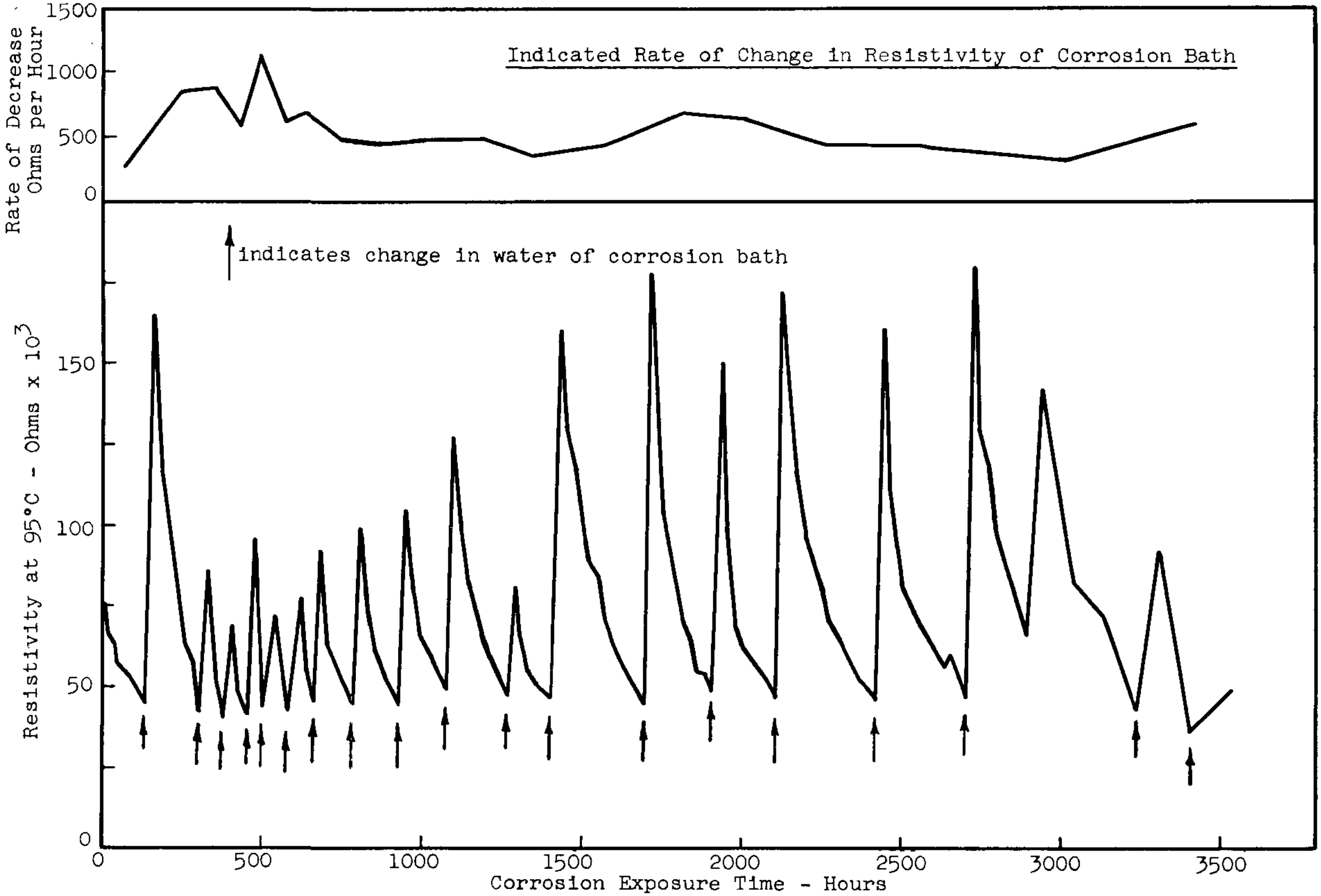


CHART 13

RESISTIVITY OF CORROSION BATH FOR SOLDER A-2

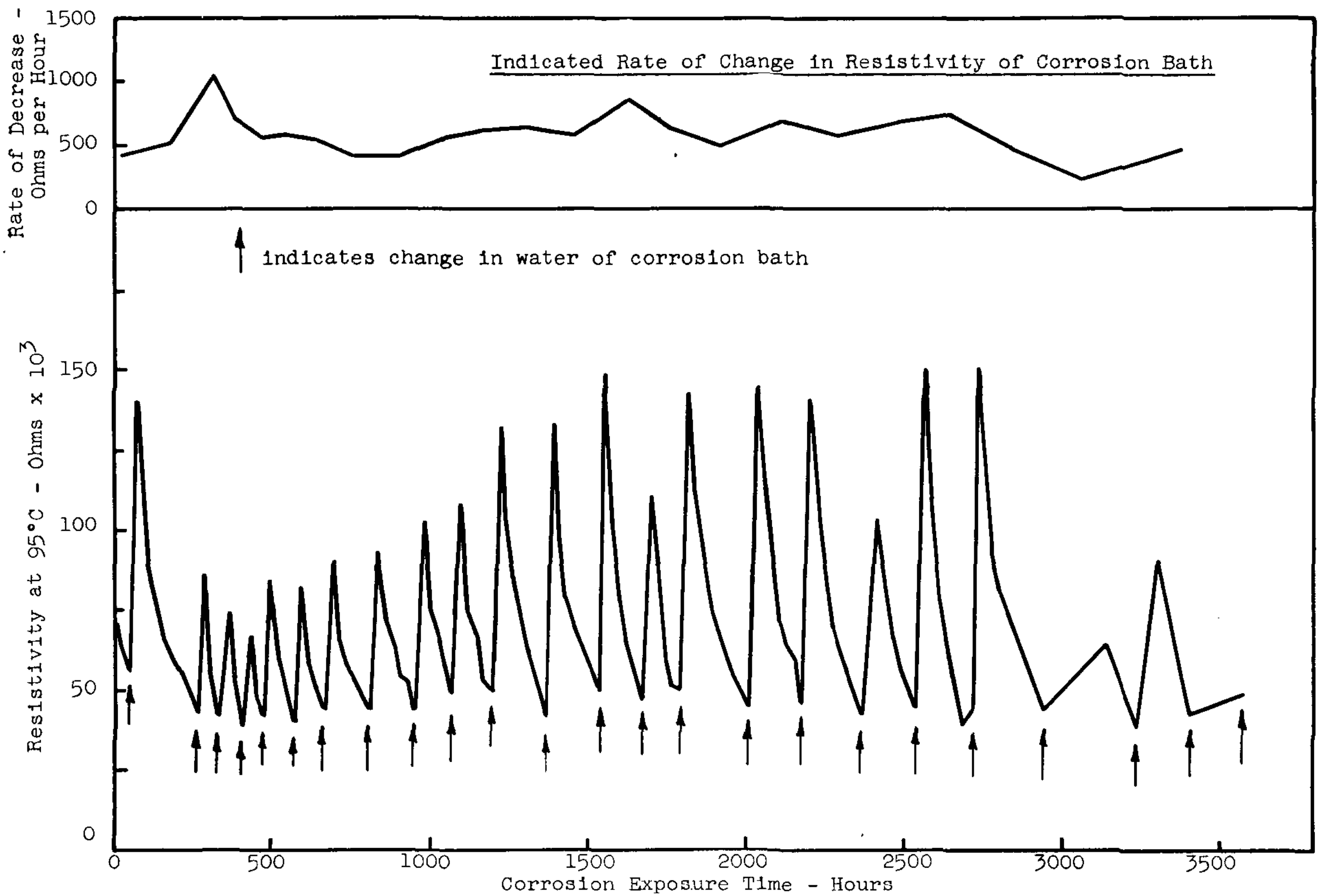


CHART 14

RESISTIVITY OF CORROSION BATH FOR SOLDER A-3

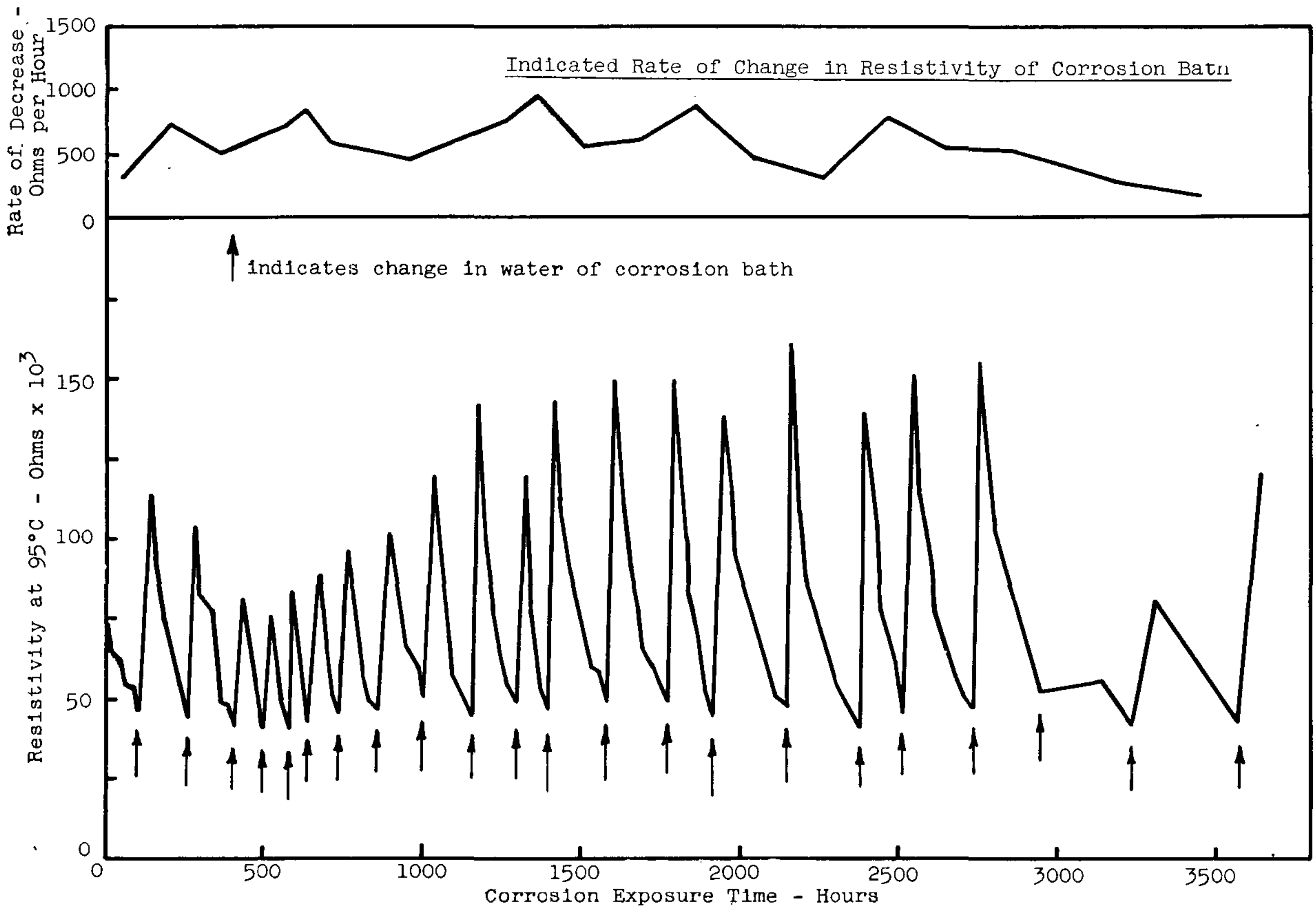


CHART 15

RESISTIVITY OF CORROSION BATH FOR SOLDER A-4

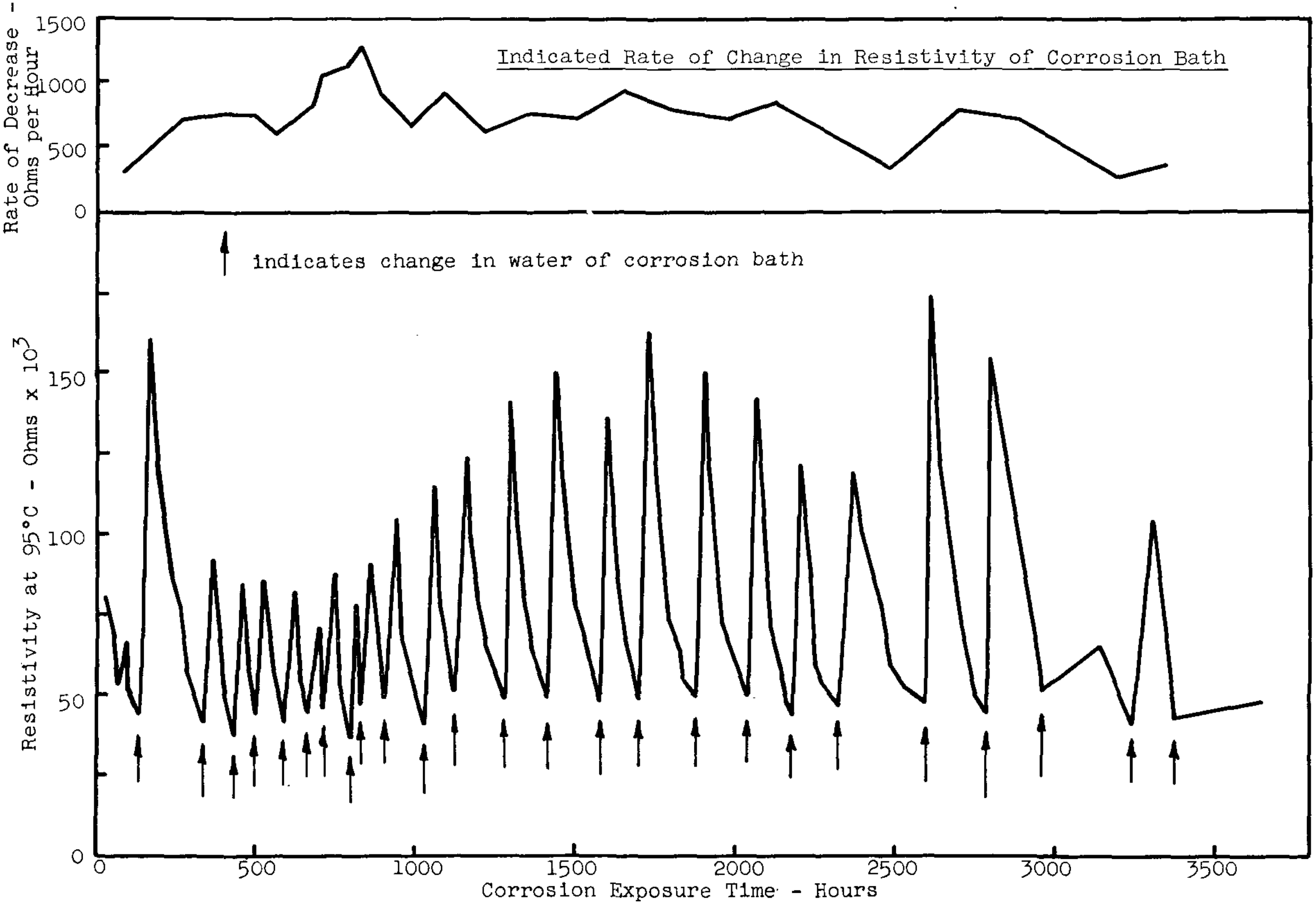


CHART 16

RESISTIVITY OF CORROSION BATH FOR SOLDER A-5

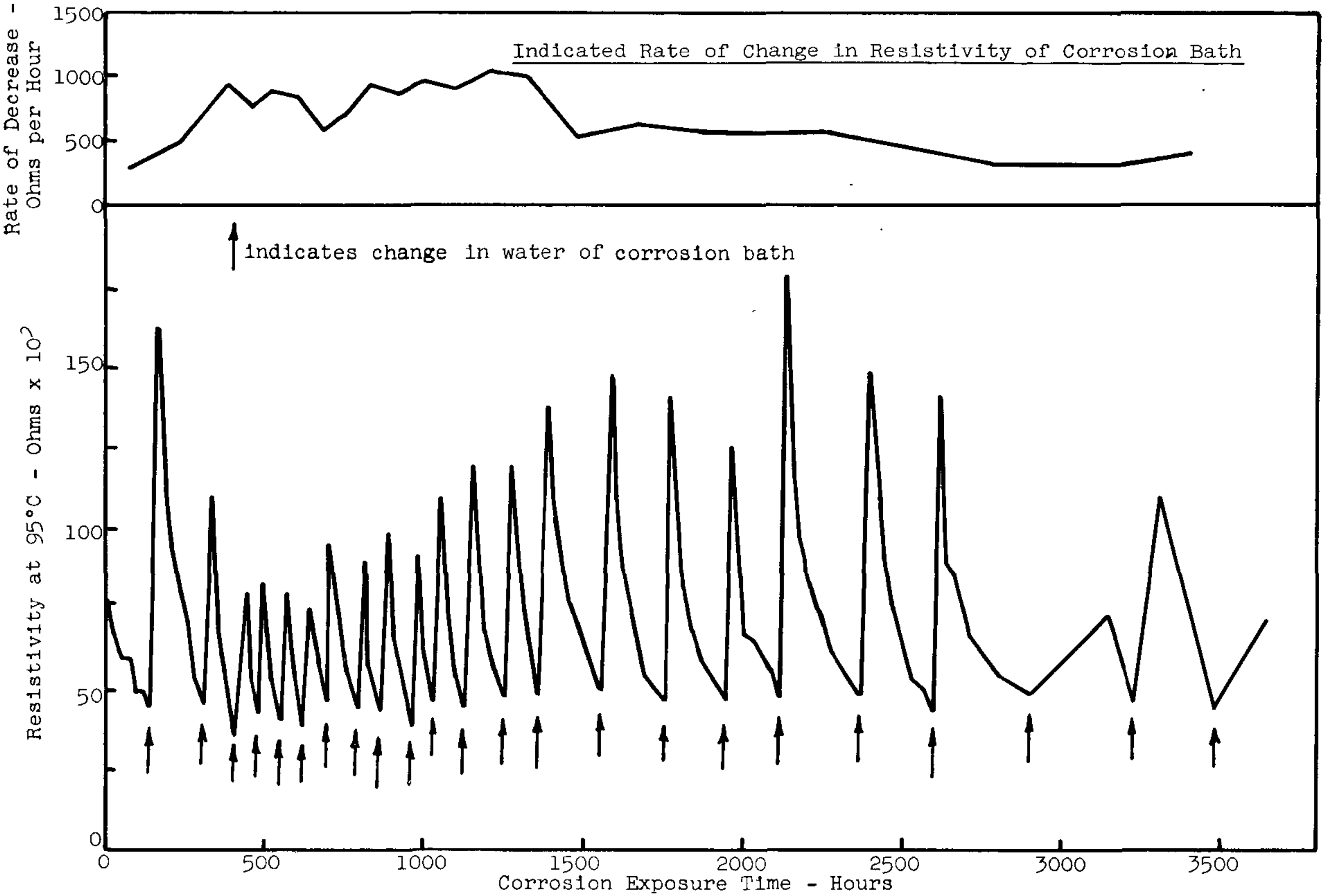


CHART 17

RESISTIVITY OF CORROSION BATH FOR SOLDER A-6

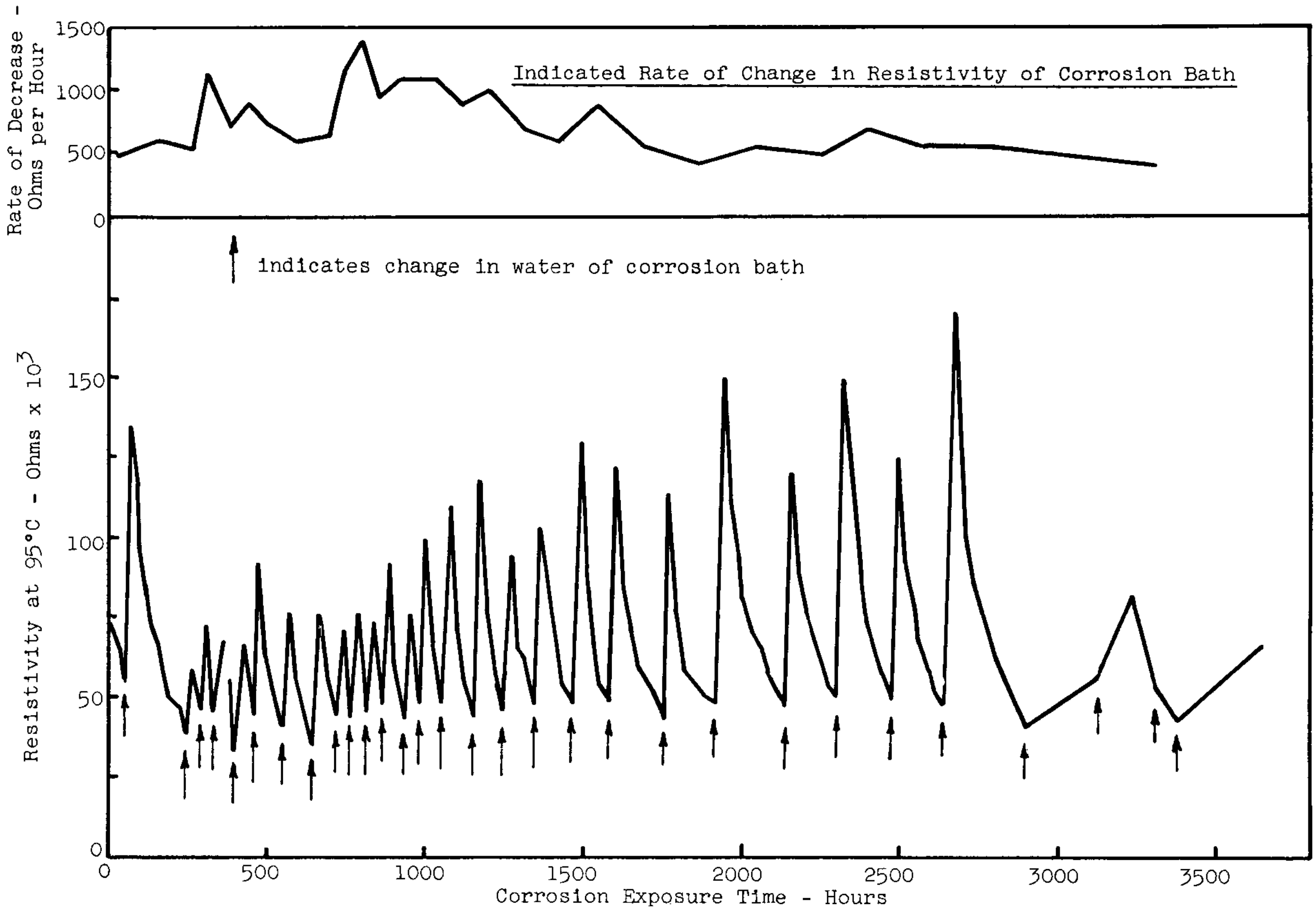


CHART 18

RESISTIVITY OF CORROSION BATH FOR SOLDER B-1

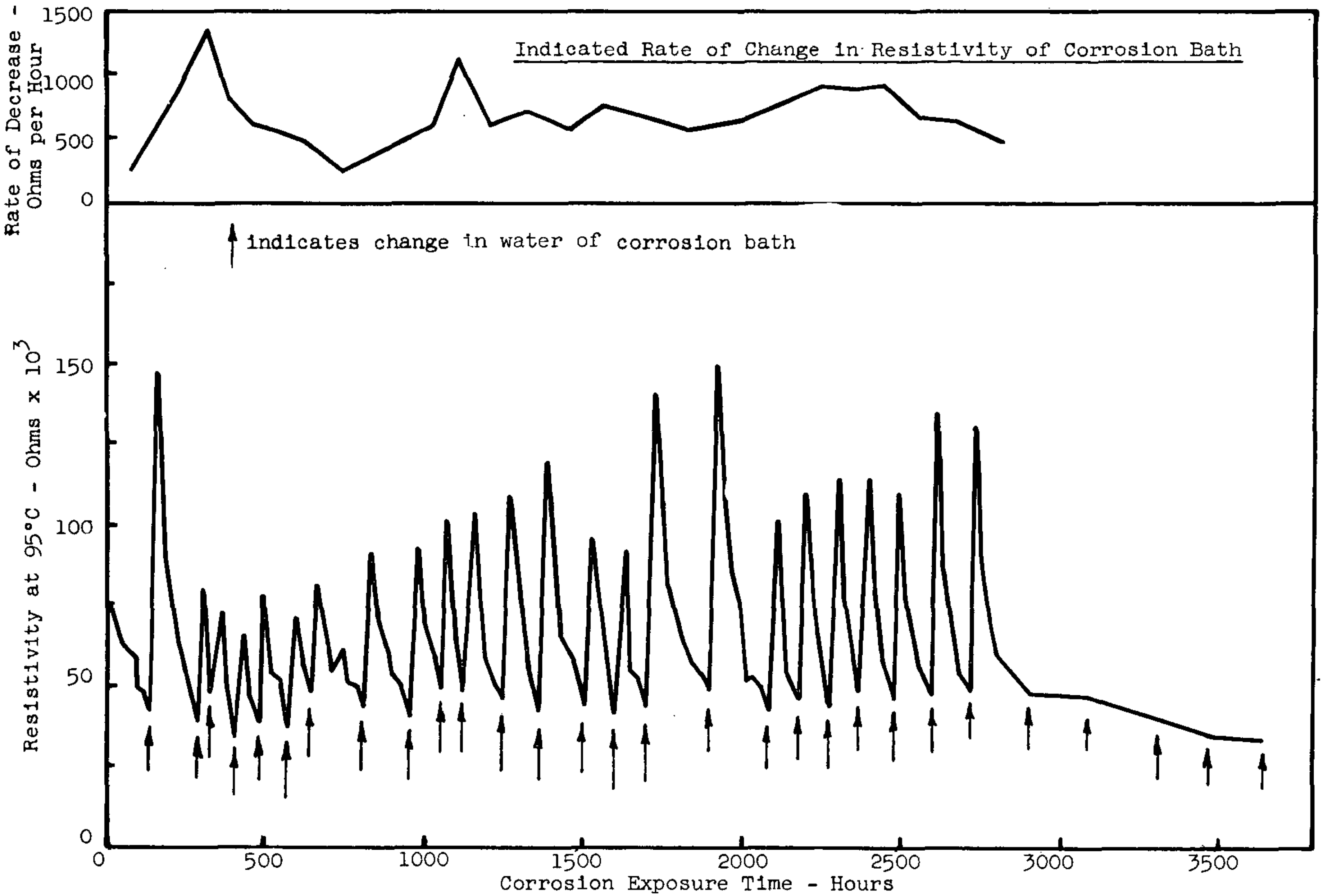


CHART 19

RESISTIVITY OF CORROSION BATH FOR SOLDER B-2

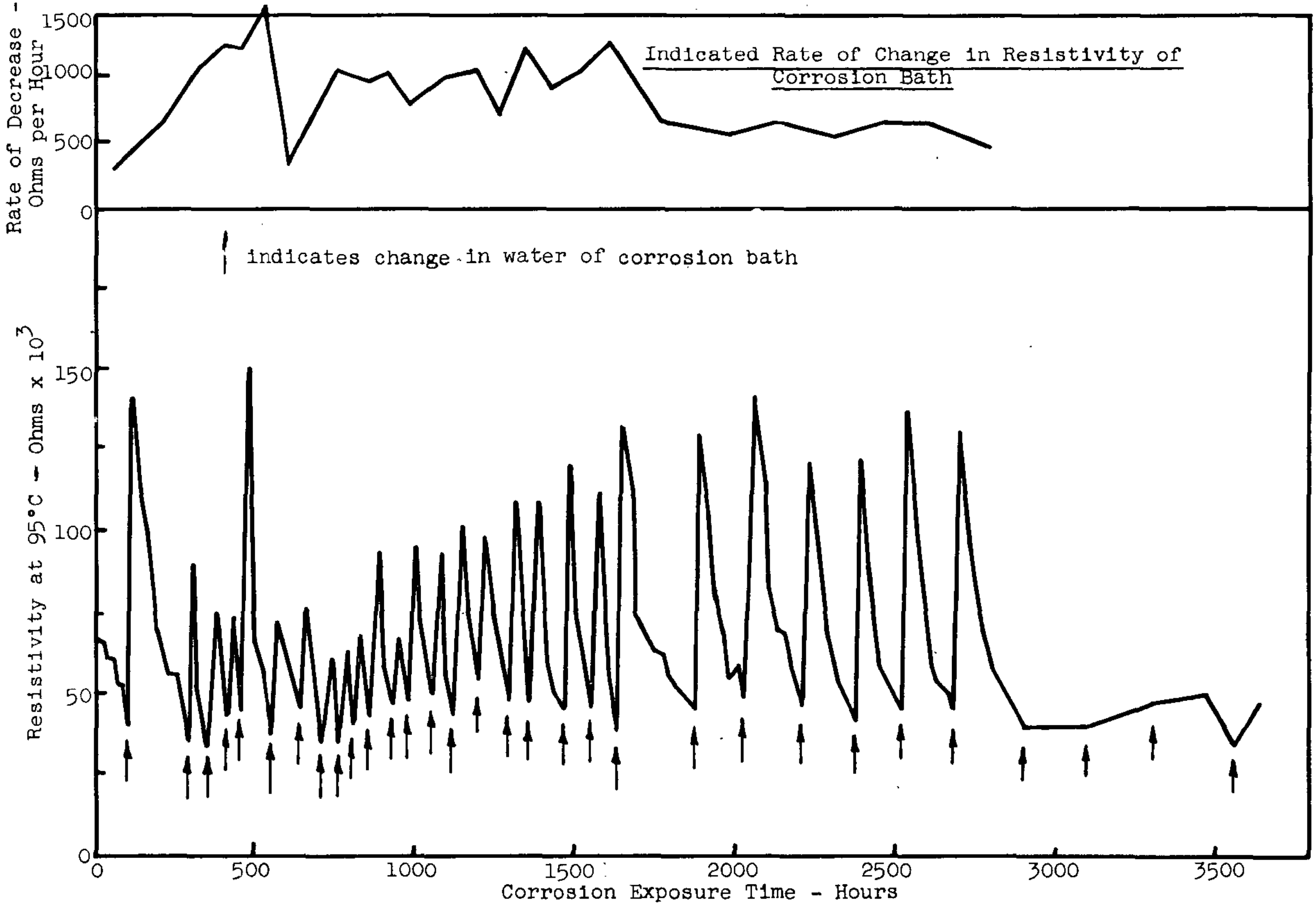


CHART 20

RESISTIVITY OF CORROSION BATH FOR SOLDER B-3

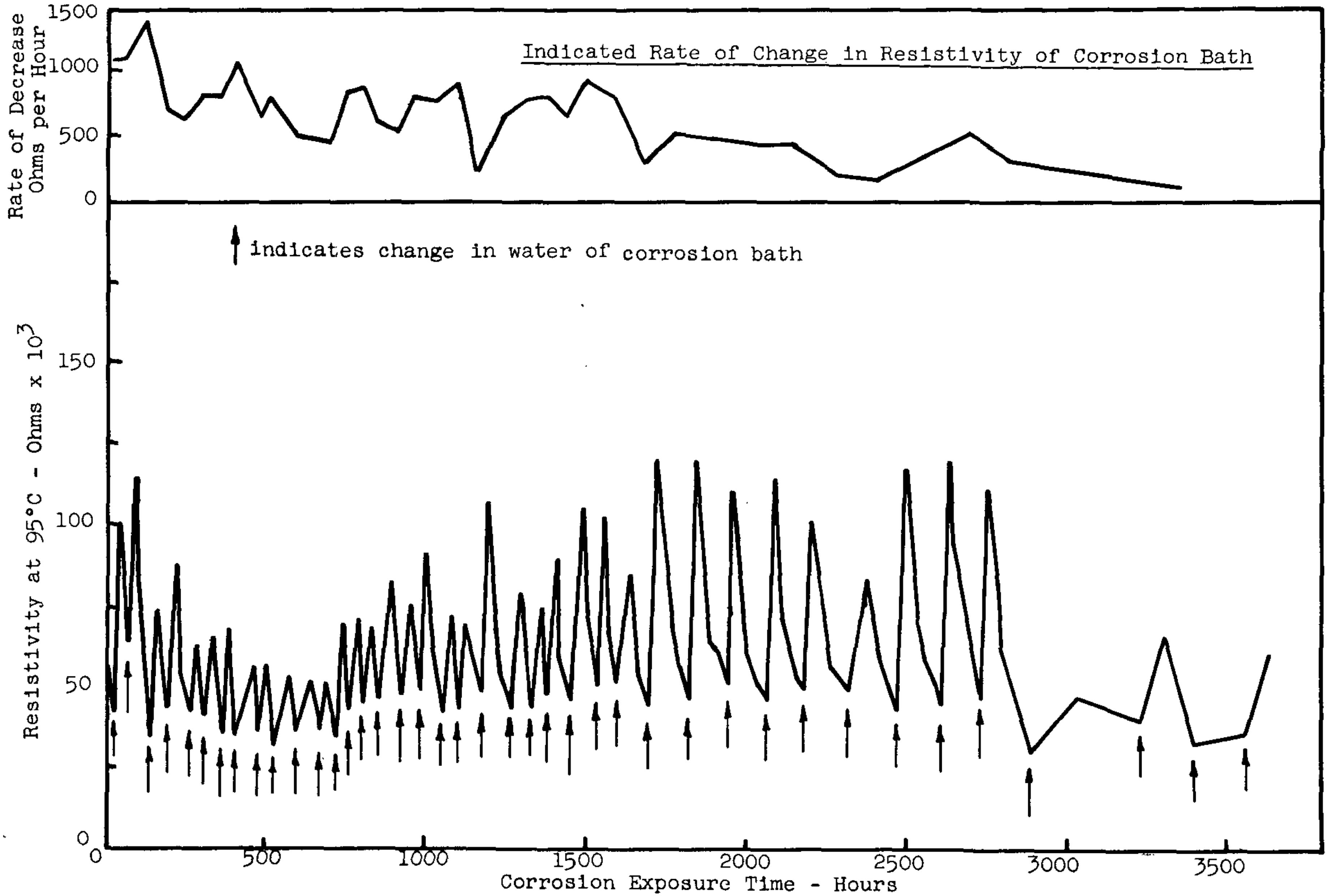


CHART 21

RESISTIVITY OF CORROSION BATH FOR SOLDER C-1

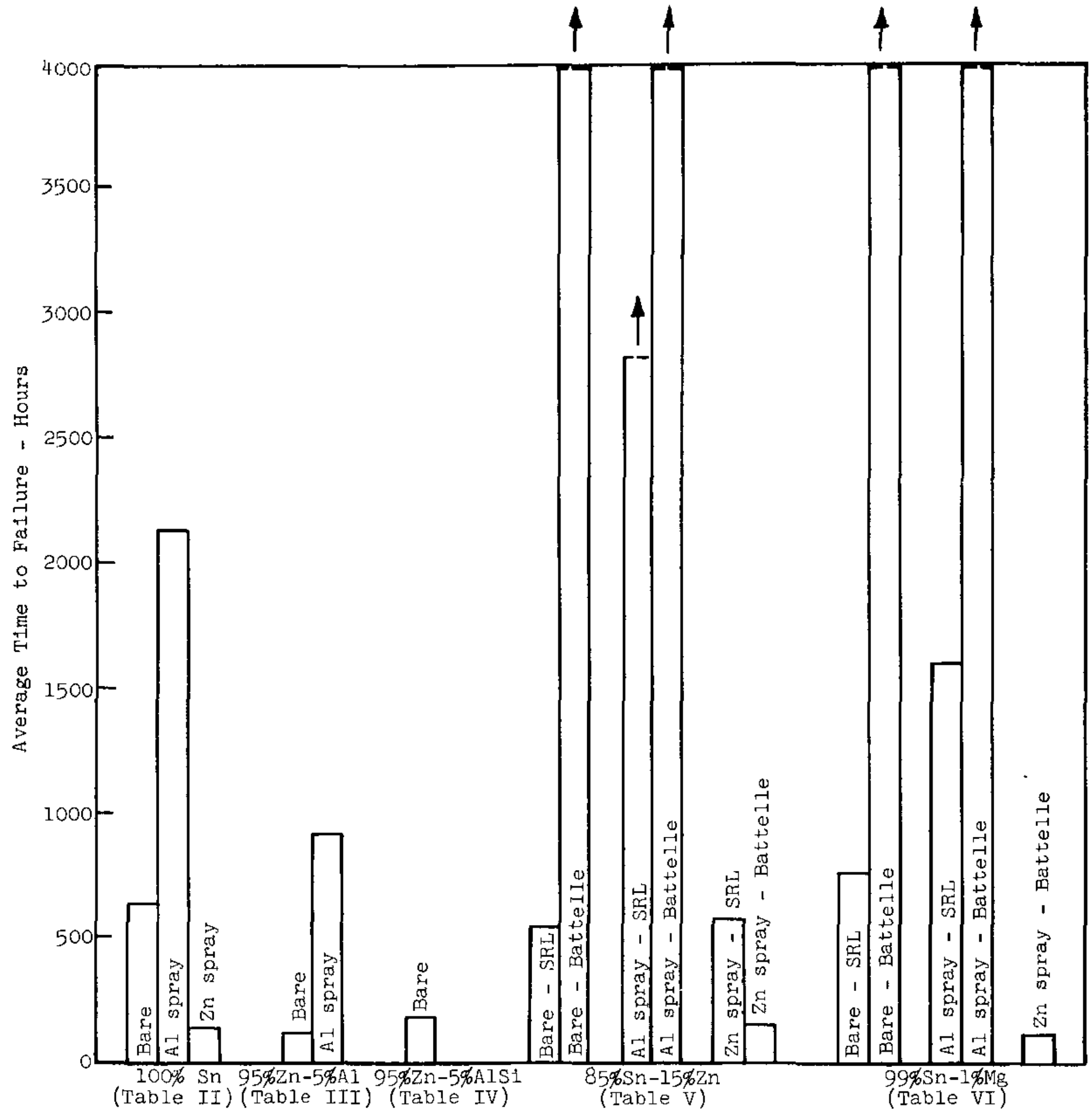


CHART 22

AVERAGE TIME TO FAILURE FOR TRAPEZOIDAL RIB-SPECIMENS
EXPOSED TO 95°C, LOW-CONDUCTIVITY, AERATED, DISTILLED WATER
AT SAVANNAH RIVER LABORATORY AND BATTELLE MEMORIAL INSTITUTE

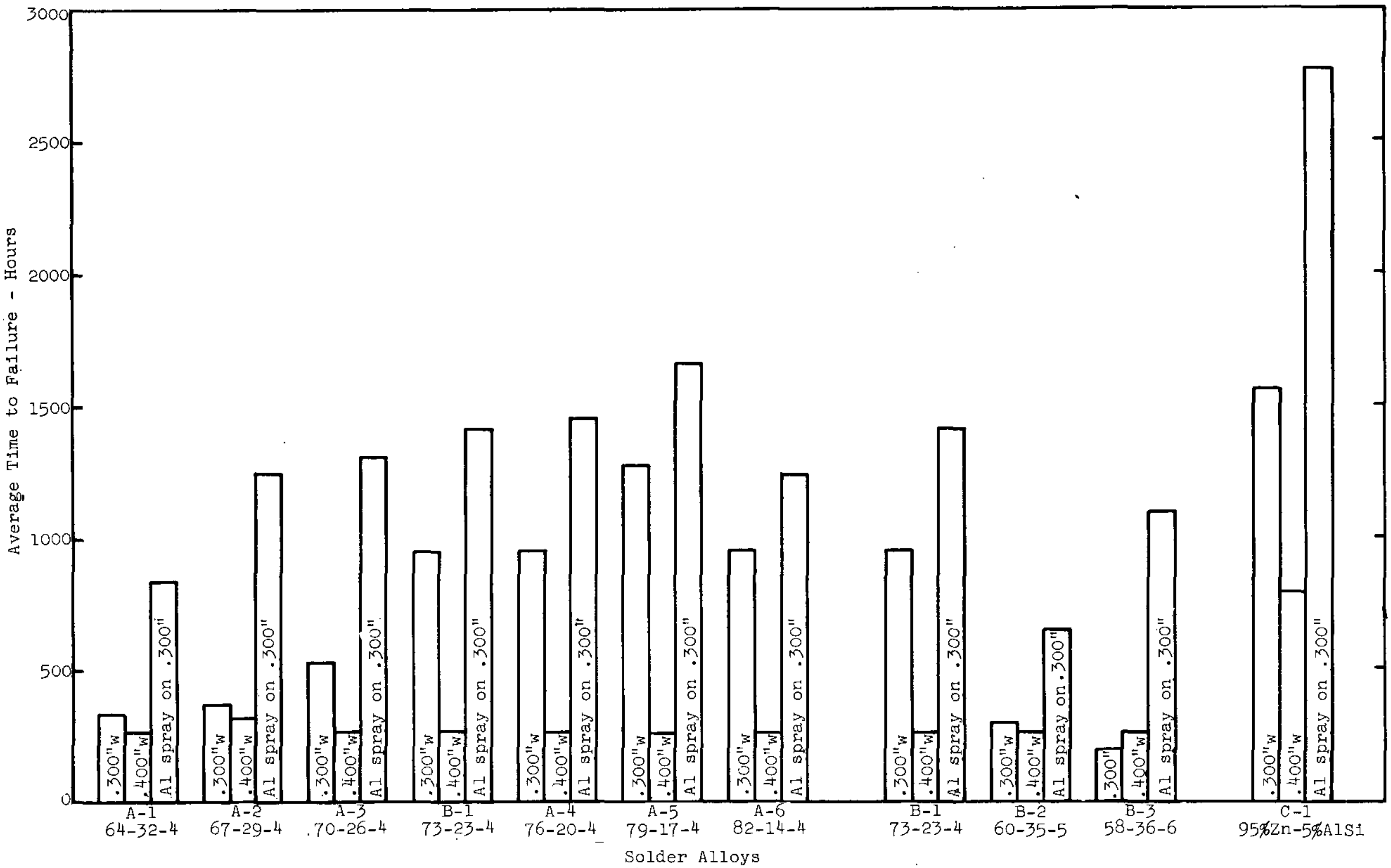


CHART 23

AVERAGE TIME TO FAILURE FOR MACHINED RIB-SPECIMENS
EXPOSED TO 95°C LOW-CONDUCTIVITY, AERATED, DISTILLED WATER
AT SAVANNAH RIVER LABORATORY