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METHODS OF POLISHING STEEL AND THEIR EFFECTS UPON THE PROTECTIVE VALUE OF ELECTROPLATED COATINGS

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ABSTRACT

To determine whether the "finish" of steel prior to electroplating affects the protective value of the plated coatings, strips of cold-rolled steel were polished with wheels to which abrasives of different grain size were glued. The resultant finishes were measured with a Profilometer and were expressed as root mean square, in microinches (millionths of an inch) of the departure of the contours from a plane surface. The finishes varied from a "superfinish," with root mean square of less than 1 microinch, to 65 microinches, produced with a 90-grain abrasive. The weight (and average thickness) of steel removed by polishing was measured.

The polished specimens were plated with copper, nickel, and chromium of controlled thickness, and were exposed to the atmosphere at New York, N. Y.; Sandy Hook, N. J.; and Washington, D. C. The extent of rusting observed at periodic inspections was expressed on a numerical scale, and the average results over a period such as 1 year were expressed as "Percentage scores."

Comparison of these scores showed that wide differences in the surface finish of the steel had no significant effects on the protective value of the plated coatings. It is possible that use of hot-rolled steel, which is more likely to contain foreign inclusions, would have yielded differences as a result of polishing.

Results with accelerated tests, such as the salt spray, hot water, ferroxyl, and condensation tests, were not as reproducible and consistent as the atmospheric tests.

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I. INTRODUCTION

The American Electroplaters' Society has cooperated with the National Bureau of Standards in a study of the effects upon the protective value of plated coatings that result from differences in the method or degree of polishing of the metal prior to plating. The complete investigation was planned to include steel, brass, and zinc-base die castings. Thus far the work has been confined principally to the polishing and plating of cold-rolled steel and exposure of the specimens to the atmosphere in three locations. These exposure tests of the steel have been completed. As this research program has been interrupted for the duration of the war, it appears desirable to publish the results of this first phase of the study.[2]

In this report the term "polishing" is used in the restricted sense generally employed in the plating and metal finishing industries, i.e., as the removal of metal from a surface by means of abrasive particles attached by adhesive to the surface of wheels or belts. While this operation is normally applied for the purpose of making the surface smoother, it has been used in this investigation to yield any desired finish, which in a given case may be rougher than the initial surface, e.g., when cold-rolled steel is polished with a 90-grain abrasive.

As will be shown, the effects of polishing cold-rolled steel upon the protective value of the coatings, as found in this investigation, are relatively small. The detailed data obtained in the polishing operations are included because they may be of interest to persons planning a more detailed study of polishing.

II. METHODS OF DEFINING SURFACE FINISH

In order to insure that specimens polished according to a given schedule were sufficiently like each other and sufficiently different from those of another set to lead to reproducible and significant results, it was necessary to employ some objective method for defining the surface finish. Because all comparable specimens were polished by about the same procedure, except for the grain size of the abrasive, it was not necessary to select a method that fully defined the surface. It was sufficient to be able to compare the contours of surfaces similarly produced.

In 1940 the ASME issued a Proposed American Standard, B46, for surface roughness, which was revised in 1942 as a proposed "American Standard of Surface Roughness, Waviness and Lay." In it the

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[2] Some of the data in this report were presented in progress reports in the Convention Proc. Am. Electroplaters' Soc. p. 54 (1941); p. 19 (1942).

FIGURE 1.—*Photomicrographic cross section perpendicular to direction of polishing, ×500.*

A, Chromium; *B*, Polished Surface; *C*, Steel. Steel specimen polished with wheel headed with 120-grain abrasive.

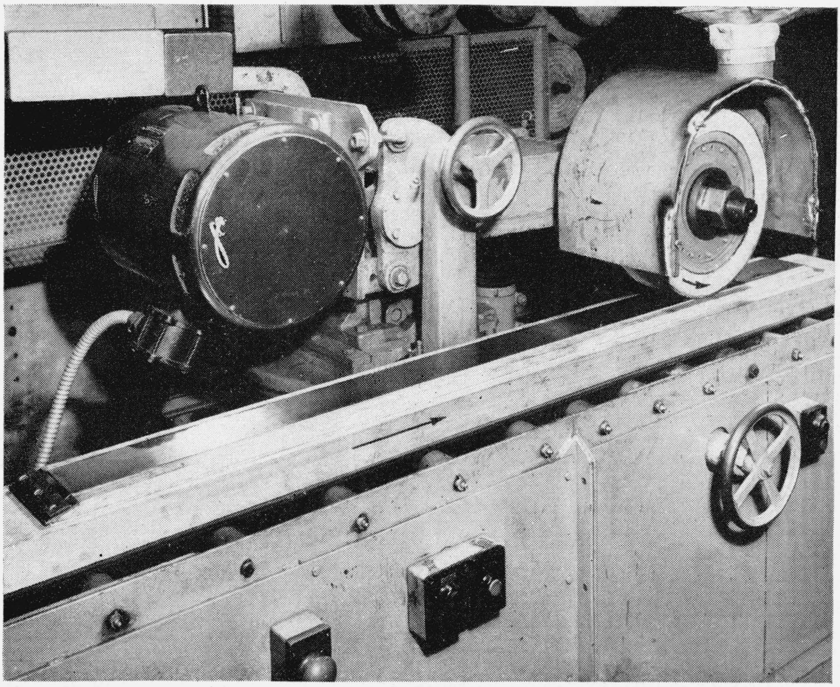

Figure 4.—*Polishing machine.*

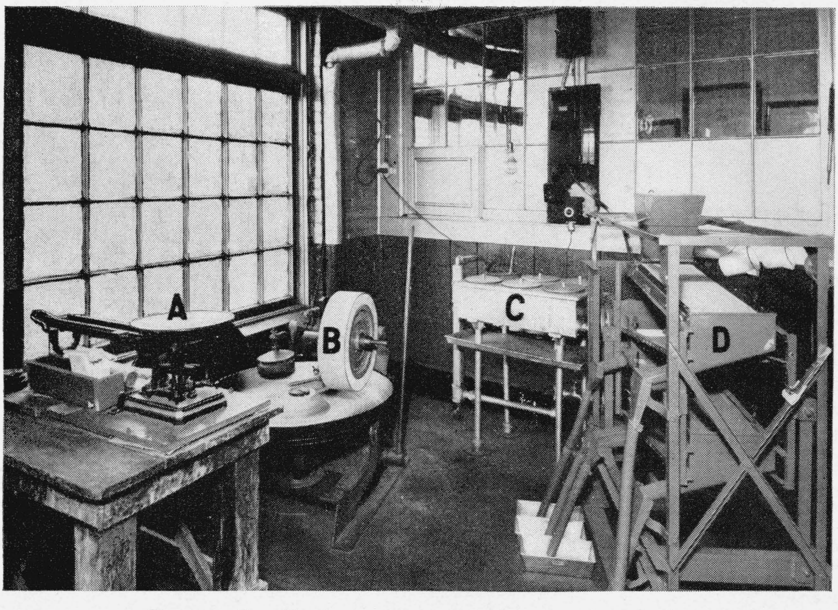

Figure 5.—*Equipment for preparing abrasive wheels.*

A, Scale; *B*, heading machine; *C*, glue heater; *D*, grain grader relevant terms are defined, and a scale of roughness is based on the root mean square [3] of the height of the irregularities from the nominal surface.

Various methods have been proposed for measuring surface roughness, including (a) microscopical examination of cross sections (illustrated in fig. 1), (b) visual or photographic examination, usually with the aid of a microscope, (c) measurements of reflectivity, and (d) tracer methods. Of these, the tracer methods are most readily applied. In these methods, a fine-pointed stylus is drawn across the surface and its movements are measured or recorded. In the Brush Surface Analyser [4] this is accomplished by means of a tracing pen, the vertical fluctuations of which are usually magnified much more than the horizontal. A typical curve is shown in figure 2. From figure 3, in which the Brush record and the photomicrograph are plotted on the same scale, it is evident that the tracer does not follow all the fine details of the contour.

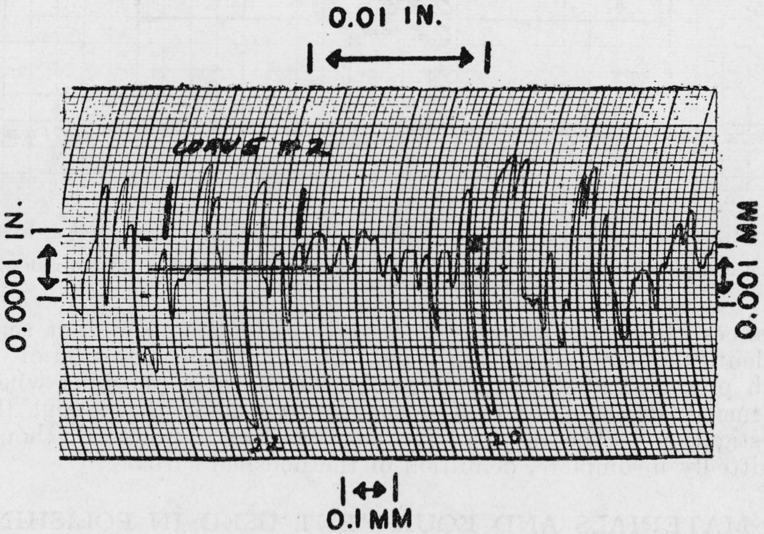

FIGURE 2.—*Brush surface analyzer chart; vertical magnification, ×3200; horizontal magnification, ×80.*

Steel specimen polished with wheel headed with 120-grain abrasive.

In the Profilometer [5] the movements of the stylus are converted electrically into scale readings, the magnitude of which expresses in microinches [6] the root mean square of the deviations of the contours from a plane. If, as is frequently assumed, the contour of a polished surface followed a sine curve, the average depth of the scratches from groove to peak would be about four times the rms value. The contours on these surfaces are usually quite irregular and do not approach closely to a sine curve, but the above relation may be used as a rough guide.

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[3] The root mean square (rms) of a group of numbers is the square root of the arithmetical average of the squares of the numbers.

[4] Made by the Brush Development Co., Cleveland, Ohio.

[5] Made by the Physicists Research Co., Ann Harbor, Mich.

[6] Millionths of an inch.

Each of these tracer methods has definite advantages and limitations. The Brush method yields a permanent record that is especially valuable in comparing the exact contours of surfaces. Because of the large magnification involved, this record usually covers only a short distance, e. g., 0.06 inch, and many observations are required to explore a surface. The Profilometer permits measurements over distances of several inches and directly yields numbers that serve to identify surfaces of a given type. To facilitate comparison of the finish produced at different stages in the life of a polishing wheel, systematic Profilometer measurements were made throughout this investigation.[7] The results have been used as a practical, though admittedly incomplete, definition of the polished surface.

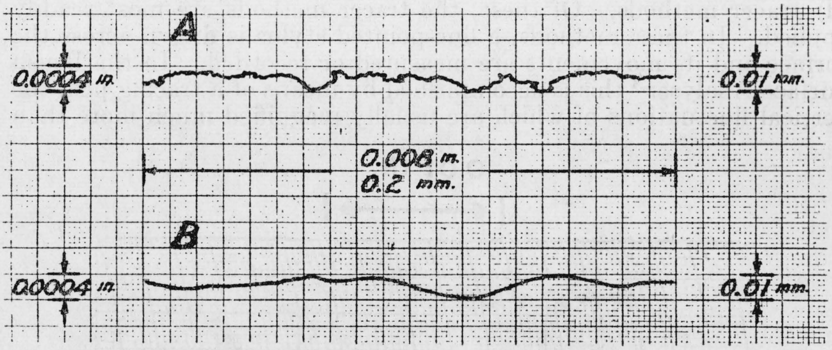

FIGURE 3.—*Comparison of profiles of adjacent areas of same specimen, both at ×400.*

A, Photomicrograph; *B*, Brush surface analyzer chart (redrawn). Steel specimen polished with wheel headed with 120-grain abrasive.

III. MATERIALS AND EQUIPMENT USED IN POLISHING

1. MATERIALS

Steel.—The steel was a "special" SAE 1010 steel described by the manufacturer as having a cold-rolled No. 3 finish and a No. 3 temper. It was supplied in flat strips, 6 feet long, 4 inches wide, and 0.031 inch thick (No. 22 U. S. gage). To complete the study, some steel strips, 6 inches wide, from the same firm were used. This steel will be referred to as 6-inch steel. In general, the results with this steel were the same as those with the original lot.

It had a smooth, bright finish, and yielded Profilometer readings of 2 to 4 microinches. It was coated with a mineral oil and packed in oiled paper.

Polishing Grains.—The polishing grains consisted of artificial aluminum oxide, with specified grain sizes from 90 to 320, which conformed in sieving tests with the requirements of National Bureau of Standards Simplified Practice Recommendation R118–40. Roughly, a grain-size number corresponds to the number of meshes per linear inch in the sieve through which most of the grain will pass.

Glue.—This was a "ground, first run, standard emery hide glue" of the grade regularly used for "heading" polishing wheels.

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[7] With the cooperation of C. E. Haven and G. M. Martin, of this Bureau.

Oil.—To produce an "oiled" finish, a mixture of 1 part of kerosine and 2 parts of medium machine oil was applied to 220 grain wheels, and a mixture of equal parts of kerosine and medium machine oil to 320 grain wheels.

Grease.—The grease finish was produced by applying tallow to the wheel, followed in some cases by a mixture of tallow and charcoal.

2. EQUIPMENT

Polishing Machine.—A straight-line semiautomatic polishing machine, figure 4, was employed. The speeds of the spindle and conveyor were adjustable, but in this study, unless otherwise noted, they were maintained respectively at 1,740 ±5 rpm and 18.5 ±0.5 ft/min. The wheel pressure was controlled by counterweights. With a wheel 4.5 inches wide, the spindle could be adjusted to provide cross polishing on the 4-inch strips up to an angle of about 10° from the direction of the conveyor belt.

Polishing Wheels.—The polishing wheels were of the compressed-canvas type and were designated by the manufacturer as having a "medium density." Each wheel was 16 inches in diameter and 4.5 inches wide. The canvas cushion was 2 inches thick, and the arbor hole was 2 inches in diameter.

Heading Machine.—The heading machine used to apply the grain to the glued wheel, shown as *B* in figure 5, had arrangements for heating the grain and for controlling the pressure of the wheel on the grain.

Glue Heater.—An electrically heated, thermostatically controlled water bath was used (*C*, figure 5).

Wheel Dresser.—A light-duty wheel-dressing machine was used to "dress," "true," and "break in" the wheels. This device is essentially a lathe that rotated the wheels at controlled speeds against the tools used for treating the wheel faces.

Wheel Balancer.—A balancing device was used to balance the wheels, and lead wire was used for adjustments.

Grain Grader.—A vibrating type grader (*D*, figure 5) with silk screens was used to "scalp" the previously used grains, that is, to remove any grain-glue agglomerates produced in previous heading operations.

Scales.—A spring scale with a capacity of 50 lb, and reading to 0.25 lb, was used to measure and control the pressure on the polishing wheel.

A beam scale (*A*, figure 5) with a total capacity of 20 kg (44 lb) and a beam capacity of 1,000 g (2.2 lb), and reading to 1 g, was used to determine the loss in weight produced by polishing a steel strip. The same scale was used to weigh the wheels and the gluepot during the heading operation.

IV. PREPARATION OF POLISHING WHEELS

The application of glue and abrasive grain to polishing wheels is commonly known as heading, and the resultant coating is called the wheel head. Before a wheel had a head of glue and grain applied to its face, it was balanced on the wheel balancer to insure smooth running in the wheel-dressing machine. To dress and true a new wheel, it was rotated in the wheel dresser at the same speed used in polishing operations, while various tools were applied to its face to remove sufficient fabric to make the wheel cylindrical. A diamond tool, carborundum wheel-dressing stones, and sandpaper were generally used in this operation.

The wheel was then sized by brushing on a 25-percent solution of glue by weight. This treatment impregnates the canvas in the sides and face of the wheel with glue, imparts a degree of rigidity, and prevents uneven absorption of the glue subsequently applied to the face in the heading operations. A relatively high concentration of glue was used for sizing in order to reduce its penetration into the canvas and thus preserve some flexibility in the wheel. The sized wheel was allowed to dry overnight, sanded on the wheel dresser, and again sized, dried, and sanded. The wheel was then weighed.

The container, brush, and glue of a specified strength were weighed. The glue was then applied by brushing on the face of the weighed wheel. The weight of glue solution applied was considered to be the loss in weight of the container. The glued wheel face was immediately rolled into the grain in the heading machine. Excess grain was trimmed off the edges of the wheel, which was reweighed. The increase in weight represented the weight of glue solution (previously determined) plus the grain. The wheel was then allowed to dry from 15 to 45 minutes, after which other weighed layers of glue and of grain were applied. The wheel was then dried for 24 to 48 hours, depending upon the temperature and humidity. After drying, a wheel head was prepared for use by removing any high spots or rough edges by hand treatment with a carborundum stone. The wheel was then mounted on the wheel dresser and the head was broken in by slowly revolving it against a hardened steel roller at a controlled pressure. This treatment caused the glued abrasive surface to crack into segments that were smaller and more uniform than those produced by the common practice of striking the surface with a pipe. Before being mounted on the polishing machine, each wheel was again balanced. When mounted on the polishing machine each new head was run on a dummy 6-foot strip for one or more passes to remove loose grain or high spots before polishing the regular strips.

When a used wheel was reheaded with the same sized grain, the head was partly dressed off with a diamond, and the wheel was headed as above. If a different grain was to be applied, the wheel was dressed off to bare canvas and resized before heading.

The glue solutions (table 1) were prepared daily from weighed quantities of glue and of water, which were mixed and allowed to stand at room temperature for 2 hours. They were then placed in covered gluepots in the heater, and heated to 150° F (66° C), at which temperature the glue was applied to the wheels. The gluepots and brushes were cleaned and scalded daily. A special type of hydrometer, known as a gluometer, was used to check and adjust the concentration of the glue solutions at 150° F.

For the application of the grease finish, "paste" heads were used on the wheels. These were headed by applying to the dried glue-sized wheel faces with a brush, two coats of a mixture by weight of 40 percent of a 19-percent-glue solution and 60 percent of a 220-grain abrasive, instead of rolling the glue-coated wheel in the grain.

Two sets were polished with a proprietary greaseless aluminum-oxide preparation. This was stated by the manufacturer to be a mixture of 220 aluminum-oxide grain and a binder containing water-soluble organic compounds. The material was supplied in round bars in sealed cans. When freshly opened, it was in a moist but firm state. When applied to a revolving cloth buffing wheel, the heat of friction liquefied the binders, and the mixture was transferred to the wheel face, where it dried. Preliminary tests showed that polishing with greaseless compound did not remove as much as 0.0001 inch of steel. To make these specimens more directly comparable with the other sets, they were first polished with regular 220 grain to remove the same amount of metal as on the other comparable sets. With the greaseless compound a packed loose-muslin buff was used at 1,170 rpm.

Table 1 summarizes the data on the heading and application of wheels with various-sized grains. These represent typical conditions that were maintained in these tests, but not necessarily the best conditions for any type of commercial polishing.

V. POLISHING PROCEDURE

The steel strip was wiped with cotton and carbon tetrachloride to remove oil, weighed, and clamped at one end to a holder on the conveyor. Side guides prevented lateral motion, but permitted the strip to expand longitudinally when heated by the polishing operation. The approximate pressure during polishing was measured with the spring balance after the wheel was lowered almost to the steel surface. The pressure was adjusted by moving counterweights, which were then clamped in position, after which the scale was removed. An adjustable stop permitted the wheel face to bear fully on the steel surface, but not to touch the adjacent, slightly lower surface of the supporting wooden plank.

The wheel, running at full speed, was lowered to the stop position, and the steel strip was then passed under it. The face of the wheel traveled in the same direction as the strip. The spindle and conveyor speeds employed throughout the tests were selected as suitable after preliminary runs, but are not necessarily the most favorable. The pressure used for each grain size was governed by trial runs in which the weight of metal removed was determined and the completeness of polishing noted. During the polishing, the conveyor traveled only in one direction, and after each pass the wheel was raised and the conveyor returned to its original position. After each pass, the strip was cooled with compressed air, which also removed any loose particles of abrasive or metal. After the final pass, the strip was cleaned by brushing and was reweighed.

The losses in weight during polishing and the Profilometer readings on the polished specimens were used as criteria of the performance of a given wheel head. Whenever these losses or readings departed from those obtained during the early use of that wheel head, and especially if they approached the values yielded by wheels with the next finer grain, use of that wheel head was discontinued, even though it might have been used commercially for considerably more polishing.

Some specimens that were "superfinished" by the Chrysler Corporation yielded Profilometer values of 0.4 to 0.7 rms microinch.

VI. TYPICAL DATA AND CONCLUSIONS ON POLISHING

Typical results obtained during these polishing studies are summarized in tables 2 to 7. From these results and other observations made in this investigation, the following conclusions may be drawn regarding metal polishing under these conditions.

1. (Table 5.) The amount of metal removed in a single pass is small, and usually corresponds to an average reduction in thickness of from 0.0001 to 0.0005 inch, according to the grain size and the wheel pressure.

2. (Table 2.) Successive passes on the same steel strip during the useful life of a wheel head (for this study), with a relatively fine grain (220) and used with low pressure (18 lb) removed a fairly constant weight of metal, but the Profilometer readings gradually decreased. This decrease, observed during the life of all wheel heads used, is probably the result of the breaking down of the individual grains.

3. (Table 4.) The amount of metal removed per pass increases with the pressure. A certain minimum pressure (in this case, about 35 lb) was necessary to polish the entire surface. If the pressure is too high, the steel may be "burnt" (oxidized).

4. With continued use and repeated heading, a polishing wheel becomes more flexible, and less pressure is required to produce polishing of the entire surface.

5. With a given grain size and with given operating conditions, there is an optimum pressure with respect to (a) completeness of polishing, (b) absence of burning, (c) weight of metal removed, and (d) effective life of wheel head. The actual pressure is usually a compromise of these values.

6. (Table 4.) The polishing pressure has no significant effect on the scratch depth (Profilometer readings).

7. (Table 3.) Continued use of a wheel head in preparation of specimens was marked by a greater rate of decrease in Profilometer values than in weight of metal removed. In general, the end of the effective life of a wheel head was marked by a sharp decrease in Profilometer values rather than by a decrease in metal removed.

8. (Table 5.) The effective life of a head with a given grain size is not greatly affected by the finish of the steel prior to polishing with that head.

9. (Table 5.) Polishing with a given grain size removes about the same amount of metal per pass and yields about the same Profilometer values, regardless of the finish prior to that polishing. The average thickness of metal removed per pass was considerably more than the approximate depth of scratch with the previous coarser polish (about four times the rms Profilometer reading). In principle, nearly this amount of metal must be removed to obliterate previous scratches.

10. (Table 1.) The shorter life of heads with finer grains may be partly caused by the smaller weight of grain on their surfaces.

11. (Tables 5 and 6.) The application of oil or grease to polishing wheel heads of a given grain size materially reduces both the amount of metal removed and the Profilometer readings. With oiled wheels, a higher polishing pressure is required to remove enough metal to eliminate scratches from preceding finishes.

12. (Table 7.) The finish produced with greaseless compound was

intermediate between that made by dry, fine-grain polishing and grease polishing. It consisted of fine, discontinuous scratches, and yielded a soft matte, or satin, finish.

VII. METHODS OF PLATING

1. PREPARATION FOR PLATING

The steel specimens were examined carefully before racking to exclude any that had obvious defects. Steel racks of the type described in previous investigations [8] [9] were used to hold the panels during cleaning and plating operations. In each rack six specimens are mounted in the same plane, so that there is about 0.25 inch between each edge and the adjoining panel or portion of the rack. With this spacing and a proper anode arrangement, the maximum variation from the average weight of coatings on any 12 specimens plated on 2 racks in one operation was less than ±10 percent.

In general, the racked specimens were subjected to the following cycle of operations prior to plating: (1) Degreasing with trichloroethylene in a vapor degreaser, (2) electrolytic alkaline cleaning, (3) rinsing in water, (4) dipping in acid, and (5) rinsing in water. If the first plating was done in a cyanide-copper solution, the specimens were also dipped into a solution of 4 oz/gal of sodium cyanide, and rinsed in water. Copper-plated specimens were prepared for nickel plating by the same treatment, except that they were dipped into a solution of 4 oz/gal of sodium cyanide and rinsed in water between operations (3) and (4). Buffed nickel-plated specimen were hand-swabbed with the alkaline cleaning solution in addition to the electrolytic cleaning operation prior to chromium plating. The details of these operations were as follows.

(a) VAPOR DEGREASING

The racked specimens were subjected in a two-compartment vapor degreaser to the following cycle: (1) Immersion in boiling solvent, (2) immersion in cool distilled solvent, and (3) immersion in vapor of boiling solvent until the specimens reached the temperature of the solvent vapors, i. e., until no further condensation occurred on the rack or specimens. Stabilized trichloroethylene was used as the solvent and periodically checked for degree of alkalinity.

(b) ALKALINE CLEANING

All alkaline cleaning was done electrolytically. Cathodic and anodic cleaning and combinations of both were used. A small amount, 0.03 fl oz (1 ml), of oleic acid was added to each 50 gal of cleaning solution when prepared, to reduce formation of spray. The compositions and applications of the cleaners are listed in table 8. Originally it was intended to use but one cleaner, designated as *N* in table 8, for cleaning the specimens prior to copper or nickel plating. Because cleaner *N*, the formula used in previous investigations, did not yield satisfactory adhesion on specimens plated with bright nickel, cleaner H was substituted for that purpose. A few sets were cleaned with cleaner *C*, which had a lower silicate content than cleaner *H*.

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[8] W. Blum, P. W. C. Strausser, and A. Brenner, *Protective value of nickel and chromium plating on steel,* J. Research NBS **13,** 331 (1934) RP712.

[9] W. Blum and P. W. C. Strausser, *Outdoor exposure tests of electroplated nickel and chromium coatings on steel and nonferrous metals,* J. Research NBS **24,** 443 (1940) RP1293.

(c) ACID DIPS

After alkaline cleaning and rinsing, the specimens were dipped into an acid solution until gassing occurred. The maximum time required for this action is recorded in table 9, together with the composition of all the dips and details of their use. No electrolytic pickling was done.

2. CONDITIONS USED IN PLATING

A Rochelle salt copper, a dull nickel, a proprietary bright nickel, and a chromium-plating solution were used. The compositions and operating conditions of these baths are listed in tables 10 to 13. The composition of each solution was maintained by frequent analyses and appropriate additions or adjustments.

The proprietary bright-nickel plating solution used was chosen by lot from the solutions in commercial use in 1941. It was of the organic addition agent type. Its installation, use, and control at this Bureau were under the supervision of representatives of the supplier.

3. BUFFING

All the dull-nickel and copper-plated specimens, with the exception of a few sets (indicated in tables 14 and 15), were "color-buffed" with full-disk loose buffing wheels, made from 64- to 68-thread muslin, and commercial lime-coloring compositions. None of the bright-nickel coatings required buffing. The loss in weight by buffing was determined in trial runs, and allowance was made in the thickness of plating so that the buffed deposits had the specified thickness (within ±10 percent). The buffing losses on the nickel coatings varied from 3 to 10 percent, and on the copper coatings they were about 20 percent.

4. SCHEDULE OF DEPOSITS

The composition and preparation of the deposits are listed in table 14 for the sets exposed in September 1941, and in table 15 for the supplemental sets exposed in April 1942. To determine the effect of initial exposure at different seasons of the year and to correlate the exposure results of the two groups of specimens, reserve panels of some of the sets prepared in 1941 were exposed with those prepared in 1942. For completeness, these sets are also listed in table 15.

VIII. ATMOSPHERIC EXPOSURE TESTS

1. CONDITIONS OF EXPOSURE

In general, five specimens of each set were exposed in each of three locations. (A few sets had only three specimens of each in each location owing to inadequacy of the original steel supply.) The locations were New York, N. Y.; Sandy Hook, N. J.; and Washington, D. C. The location of the racks, their construction, and the method of mounting the specimens are the same as those previously used and described in earlier papers of this Bureau.[10]

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[10] W. Blum, P. W. C. Strausser and A. Brenner, *Corrosion-protective value of electrodeposited zinc and cadmium coatings on steel,* J. Research NBS **16,** 185 (1936) RP867. See also references given in footnotes 8 and 9.

2. METHOD OF INSPECTION AND RATING

Inspections of the specimens exposed in the fall of 1941 and in the spring of 1942 were made by the members of the AES Research Committee and other interested persons. The average number of persons at each inspection was seven.

The method of rating was described in detail in other reports (see footnotes 8, 9, 10). Each inspector assigned to each specimen a numerical rating from 0 to 5, based on the percentage of the surface that had failed. Because only steel specimens were included in this phase of the project and there was no marked evidence of other failures (such as cracking, peeling, or blistering), the ratings were determined solely by the area of the surface rusted. The percentage total scores for a given period represent the ratio of the average scores during that period to a perfect score, and hence correspond to the relative average protective value of the coatings for that period.

3. RESULTS OF EXPOSURE TESTS

The results of the inspections are given in tables 16 to 22, and in figures 6 and 7. In figures 6 and 7 the course of the corrosion is plotted against elapsed time for the buffed and bright nickel coatings, respectively, in the three locations. The relation between figure 6

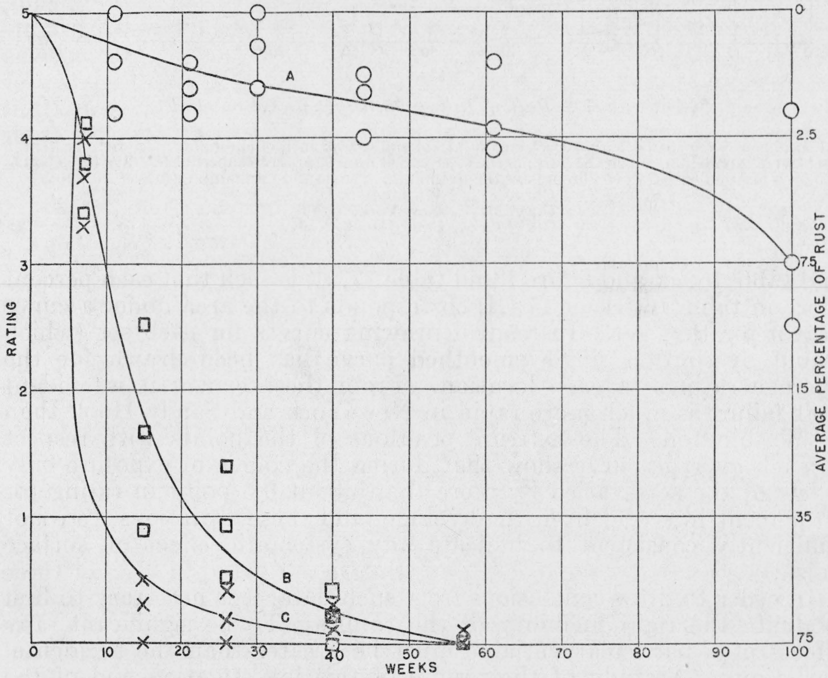

FIGURE 6.—*Rate of failure of buffed dull nickel on steel.*

All specimens were coated with 0.00075 inch of nickel and 0.00002 inch of chromium. In each location, 8 sets were exposed, on which the finish of the steel varied from 90 grain to superfinish. The three points in each location for each period represent the maximum, average and minimum ratings of the 8 sets.

Curve A. ○ Washington, D. C.
Curve B. □ New York, N. Y.
Curve C. × Sandy Hook, N. J.

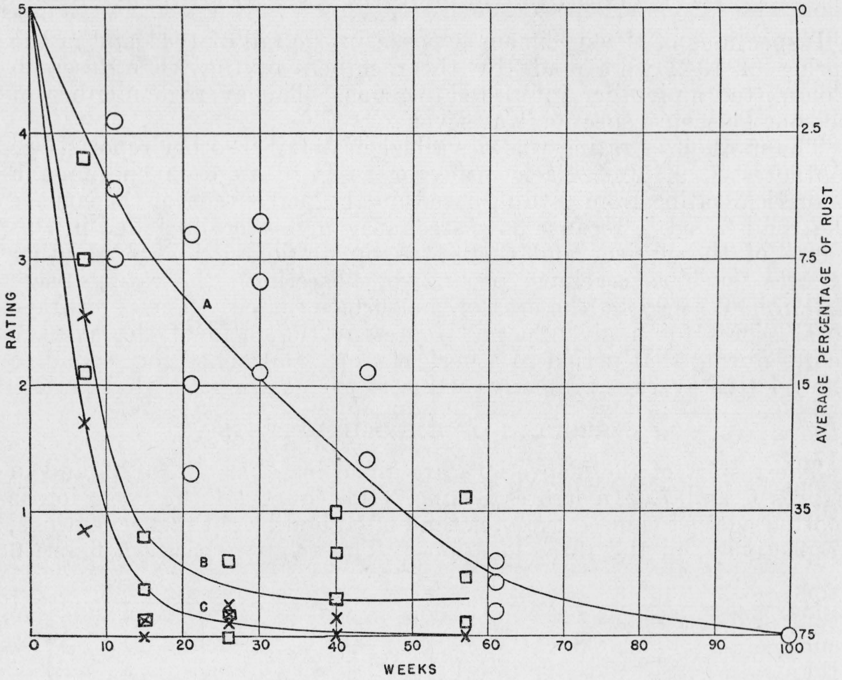

FIGURE 7.—*Rate of failure of bright nickel on steel.*

All specimens were coated with 0.00075 inch of nickel and 0.00002 inch of chromium. In each location, 8 sets were exposed, on which the finish of the steel varied from 90 grain to superfinish. The three points in each location for each period represent the maximum, average and minimum ratings of the 8 sets.

Curve A. ○ Washington, D. C.
Curve B. □ New York, N. Y.
Curve C. × Sandy Hook, N. J.

and table 16, *A*, and figure 7 and table 17, *A*, is such that each percent score in table 16, *A*, or 17, *A*, corresponds to the area under a curve drawn for that set. Instead of drawing curves for each set (which would overlap) a single smoothed curve has been drawn for the average ratings in each location. From these curves it is evident that failure is much more rapid in New York and Sandy Hook than in Washington. The extreme positions of the points with respect to each average curve show that during the course of exposure only a few of the sets varied by more than about 0.5 point in rating (or 10 percent in score) from the average, and these variations were not sufficiently consistent to indicate any systematic effect of surface finish.

In order to draw conclusions from such data, it is necessary to first evaluate the reproducibility of the results. To be significant, any effects of a particular variable must be greater than the accidental variations. A study of the results of this investigation and of the much larger number of inspection data from previous similar exposure tests indicates that in any single location a given score must vary by about 10 percent from the average of comparable sets to be significant, and for the mean of three or more locations, by at least 5 percent from the average.

When this criterion was applied to the above-mentioned tables, no conclusive evidence was obtained of a consistent effect of the polishing upon the protective value of the plated coatings on cold-rolled steel. For example, (table 16, *A*) with 0.000 75 inch of buffed dull nickel and 0.000 01 inch of chromium, eight sets ranging from a 90-grain finish to a superfinish, showed no variations as high as 5 percent from the average of the three locations. The supplemental exposure tests (table 16, *B*) have been divided in two parts, according to the year the specimens were prepared. This distinction was made because, for no known reason, of comparable sets exposed in 1942, those plated in the first year of this project failed somewhat more rapidly than those plated later. It is not believed, however, that the former panels deteriorated in storage, as they were protected by wax paper from the surrounding atmosphere. In each group, the deviations from the average are all less than 5 percent.

With seven similar sets plated with bright nickel and chromium (table 17, *A*) there were no deviations of more than 5 percent from the average of three locations. In the supplemental tests (table 17, *B*), when divided similarly to table 16, *B*, there were some variations as high as 7 percent from the average of three locations, but these variations showed no direct relation to the preparation of the steel. No significant effects of polishing have been observed.

Comparison was also made of those sets on which the final polish was the same, but had been preceded by different prior polishing operations, which consequently removed different depths of metal from the surface. The results (tables 18 and 19) showed still smaller differences than were observed between different polishes applied directly to the steel.

No differences were observed in the behavior of specimens cut from the 4-inch and 6-inch steel strips, or of those prepared by the different cleaning procedures that yielded adherent deposits (table 21).

The results (table 22, *A*) with those few sets in which the thickness of bright nickel, or of copper plus bright nickel, was varied from 0.000 40 to 0.001 25 inch, showed a consistent increase in protective value with thickness, just as was observed in previous exposure tests.

Of those few sets (table 20) in which unbuffed dull nickel was compared with buffed nickel, the unbuffed specimens showed a marked superiority (+21%) only on the unpolished cold-rolled steel. On sets polished with 150 or 220 grain, the buffing of the nickel had no large effect.

The sets with buffed copper under bright nickel (table 22, *A*) were distinctly better (+21%) than those with bright nickel of the same total thickness applied directly to the steel; and were equal to those with buffed dull nickel of the same total thickness. This result is different from the previously reported detrimental effect of copper under buffed dull nickel. These results were confirmed with additional sets with copper followed by buffed or bright nickel that were included in the supplemental exposure tests, table 22, *B*.

4. DISCUSSION OF RESULTS

It has been generally believed that plated coatings of a given thickness are more porous and hence less protective when applied to rough surfaces than to smooth or highly polished surfaces. This belief was not borne out in these tests. Several causes may have contributed to this apparent contradiction.

1. The steel used in this study was cold-rolled and the surface was free from oxide or scale such as are normally present on hot-rolled steel. A given method or degree of polishing might not leave as continuous a metal surface on hot-rolled steel as on the steel here used.

2. This steel was of a special grade that normally contains less foreign inclusions than some other grades of steel, especially hot-rolled. It has been reported that these inclusions are more numerous below than on the surface and are therefore increasingly exposed by the successive polishing operations. No such effects were observed with the steel used in this study.

3. For most decorative plating, it is customary to produce a final bright surface. If, therefore, a deposit of nickel is applied to a relatively coarse surface, it will be necessary to "cut" and "color" the nickel to achieve a smooth, bright surface. In that process an appreciable amount of nickel may be removed from the ridges, making the coating there thinner and possibly cutting through it. Under such conditions greater porosity might be expected for coatings applied over rough surfaces than over smooth. In this investigation no attempt was made to smooth the nickel surfaces by cutting down. The slight color-buffing that was applied to the dull-nickel deposits did not eliminate the scratches derived from the base metal or appreciably reduce the thickness of the nickel, even locally.

The most similar study to this one is that described by W. L. Pinner.[11] He polished panels of (a) hot-rolled SAE steel 1085, (b) commercial cold-rolled SAE steel 1010, and (c) "perfect" cold-rolled steel 1010, with various abrasive grains, plated them with nickel, and subjected them to the salt-spray test.

With the hot-rolled steel (a) and the commercial cold-rolled steel (b) he found that a decrease in grain size of the abrasive, e. g., from 90 to 220 grain, improved the protective value of the nickel coatings. This effect was most marked when greased wheels were used for the final polish. With the perfect cold-rolled steel, no effect of grain size was observed by him except with 90 grain, which yielded a poorly protective coating.

The results of Pinner on the perfect steel are consistent with those of this investigation, except for the low rating with the 90-grain abrasive. This small discrepancy may involve the use of the salt spray in Pinner's tests, and of atmospheric exposure in the present tests. It is possibly significant that in table 16, with buffed dull nickel, the 90-grain specimens showed the average behavior in the atmosphere, but a very much larger number of rust spots in the salt spray than did other sets in this table.

The conclusions of W. M. Phillips [12] and of A. W. Hothersall and R. A. F. Hammond [13] that roughly polished surfaces yield more porous deposits, may also have involved more inclusions in their steel than were in the steel used in this study.

The conclusions reached in this study, that wide variations in the polishing operations and in the contours of the steel surface prior to plating have no significant effect on the protective value of the plated coatings, may therefore apply only to steel that is initially free from scale and inclusions and that has not been polished to pro-

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[11] Convention Proc. Am. Electroplaters' Soc. p. 137 (1940).

[12] Conv. Proc. Am. Electroplaters' Soc. p. 249 (1936).

[13] Trans. Electrochemical Soc. **73,** 449 (1938).

duce a smooth surface after plating. More extensive studies are required to determine the effects of polishing under other conditions.

IX. ACCELERATED-CORROSION AND POROSITY TESTS

In general, the purpose of accelerated-corrosion tests of coated metals is to determine in a short time the *relative* protective value of two or more coatings. In order to expedite corrosion some conditions of the test, such as the corroding medium or the temperature, must be different from those in the normal or expected conditions of service. Because of such variations, the actual results of the exposure test do not usually approach closely to those obtained in service. If, through research or experience, a correlation has been found between a given type of service and the results of an accelerated test, the latter may be used in research or in specifications relating to similar conditions of exposure. The exposure tests discussed above gave an opportunity to compare accelerated tests with atmosphere tests.

The failure of coatings of noble metals, including copper and nickel on steel, is associated with porosity of the coatings. It has been shown that the most effective means of decreasing the porosity is to increase the thickness. The usual porosity tests involve application of a reagent that will not attack the coating but will attack the base metal and yield visible evidence of such attack. Four such methods, namely, salt-spray, ferroxyl, hot-water, and moisture-condensation tests, were applied in this investigation to reserve specimens of the sets subjected to exposure tests. The results may be summarized as follows:

1. SALT-SPRAY TEST

This test was conducted with a 20-percent solution of sodium chloride at 95° F. in the box designed and used at this Bureau. The specimens were hung vertically,[14] and their positions were changed every 24 hours to eliminate any effects of possible nonuniform distribution of the fog. (Owing to the limited supply of the plated specimens, usually only a few of each set were subjected to each type of test.) Inspections were made and the numbers of rust spots were recorded at 24-hour intervals.

It was found that the results of the salt-spray test were not nearly as reproducible as the exposure tests of similar specimens. In the latter tests there were few sets of five samples in which there was any large deviation in the extent of rust on individual specimens. In the salt-spray test, however, at the end of 100 hours, 1 specimen might show 30 to 40 rust spots and 2 others of that set only 1 or 2 spots.

In addition, it was found that when the salt-spray test was applied to these specimens for 336 hours (14 days) most of them showed a large increase in the number of spots, in some cases to 100 or more per specimen, although some showed practically no spots after the long exposure.

This behavior suggested that the salt spray was slowly attacking the coatings and producing pores where none existed previously (just

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[14] Since these tests were conducted, it has been found that more significant results are usually obtained in the salt spray by mounting the specimens at an angle, such as 15°, from vertical. These tests were conducted without the control of fog that is now specified.

as has been reported for the ferroxyl test). At first, this possibility was discounted by experiments made at this Bureau some years ago, from which it was then concluded that the rate of attack of nickel in the salt spray is negligible.

As a further check, weighed pieces of detached nickel foil, deposited respectively from the dull and the bright-nickel baths, were exposed to the salt spray for 8 days. The dull nickel acquired some brown stains and the bright nickel some green stains. These were cleaned off by light rubbing with magnesium oxide and the specimens were dried and weighed. The loss in weight of the dull nickel corresponded to 0.0020 g/dm^2 of exposed surface, and of the bright nickel to 0.0076 g/dm^2. If these losses had represented uniform attack of the entire surface, and if the foil had been 0.001 inch (0.025 mm) thick, the loss in 8 days would have corresponded to about 1/1000 of the weight of the dull nickel, or to 1/250 of that of the bright nickel. With attack on only one side (as occurs with an adherent deposit), it would have required 16,000 days (over 40 years) to completely dissolve the dull nickel and about 10 years to dissolve the bright nickel. This slow rate justifies the former conclusion that the total attack of nickel in the salt spray is negligible.

Examination of the corroded foils showed that they had not been uniformly attacked, but that numerous fine holes had been produced in the foils, which by visual examination, were apparently free from pores before the test. This behavior, which is similar to that observed with nickel in contact with ferricyanide (ferroxyl test) or with iodine, is a definite evidence that an apparently dense nickel deposit may not be homogeneous. The holes may have been produced by solution of a very thin film of nickel that had bridged over pores that were present during the initial stages of deposition. Another possibility, confirmed by a few microscopic observations, is that the deposits may contain inclusions of basic salts, which are dissolved out by certain reagents.

These results cast doubt upon the value of the salt-spray test for detecting pores in nickel coatings. Pending more exhaustive study, it is logical to take as a tentative measure of porosity the results of a relatively short period, such as 100 hours, in the salt-spray test. When this criterion was applied to the results with the polished and plated specimens, no correlation was found with the exposure tests. The two sets of dull nickel that showed large numbers (40 and 20) of spots in the salt spray, and the one of bright nickel (30 spots) were from sets that showed no marked failure in the exposure tests.

2. FERROXYL TEST

Because it had been shown by numerous investigators that the ferricyanide reagent commonly employed in the ferroxyl test attacks the nickel and produces pores, P. W. C. Strausser[15] developed a test in which paper saturated with a solution of sodium chloride and gelatin was applied to the surface and was subsequently "developed" in a ferricyanide solution. In the present study, mostly with deposits 0.000 75 inch thick, ferroxyl tests were made with the regular method and the dilute reagent, containing 60 g/liter of sodium chloride, 0.5 g/liter of potassium ferricyanide, and 10 g/liter of agar. Specimens

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[15] P. W. C. Strausser, Convention Proc. A. M. Electroplaters' Soc. p. 194 (1939).

from 25 sets with a wide variation in polishing and plating, showed from zero to nine spots, with an average of only about two spots per specimen. On these relatively thick coatings it is apparent that the dilute ferroxyl reagent disclosed very few if any pores in the time of the test (10 minutes). The numbers of spots showed no correlation with the exposure tests.

3. HOT-WATER TEST

In this test the plated specimens were heated for 6 hours in distilled water kept at 194° to 203° F, and then removed and allowed to dry in the air. Any visible rust spots were then recorded. To avoid attack of glass by the water, which might increase the pH of the water, a tinned-steel container was used for hot water.

As previously reported by Strausser (see footnote 15) and others, the hot-water test generally yielded smaller numbers of spots than did the salt spray or ferroxyl. On only one set were more than five spots per specimen revealed. Of three specimens of this set the numbers of spots were 0, 12, and 15, showing poor reproducibility. No correlation was found with the exposure tests.

4. MOISTURE-CONDENSATION TEST

This test was recently used at this Bureau [16] in a study of the protective value of painted coatings on steel. The specimens are cooled in air of high humidity so that moisture condenses on them for 5 hours, then allowed to stay wet for 18 hours, and finally dried for 1 hour in warm dry air. These stages constitute one 24-hour cycle.

This test proved to be slower and less discriminating than the other porosity tests. In 50 days, practically no rust spots appeared on the buffed dull-nickel specimens plated directly on the steel, although some rust spots appeared on the bright-nickel deposits within about 10 days. This method does not appear to be a practical method of testing plated metals.

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[16] R. E. Pollard and W. C. Porter, NBS Report BMS44 (April 8, 1940).

TABLE 1.—*Heading and operation of wheels*

[Minimum drying time 24 hours at room temperature. All heads consisted of 2 coats of glue and grain, the latter applied with 1 light rolling and 3 pressure rollings]

Grain size	Glue, concentration by weight	Average weight of glue plus water per head	Average weight of grain per head	Drying time between first and second coats	Break-in run before use	Pressure used in polishing	Average effective polishing life of head
	Percent	*oz*	*oz*	*min*	*ft*	*lb*	*ft*
90	33	3.4	7.4	45	30	35	214
120	30	2.5	6.3	45	18	30	132
150	30	2.6	5.7	30	18	25	126
180	25	2.4	4.4	30	12	25	113
220	25	2.0	3.7	20	12	25	70
320	25	1.6	3.0	15	6	25	38

TABLE 2.—*Effect of successive passes of a wheel with a dry 220-grain head on one steel specimen*

[Polishing pressure, 18 lb]

Pass number	Metal removed per pass		Total thickness of metal removed at end of last pass (×.000 01 in.)	Profilometer reading (rms microinches)		
	Ounces per strip	Equivalent thickness (×.000 01 in.)		Max.	Min.	Mean
1	0.24	19	19	30	25	28
2	.21	16	35	30	22	26
3	.24	19	54	27	18	23
4 to 8 (avg.)	.23	18	144	31	19	25
9 to 18 (avg.)	.23	18	324	28	15	22
Average	0.23	18				25

TABLE 3.—*Effect of continued use of a wheel with a dry 150-grain head on steel specimens*

[Polishing pressure 25 lb. New strip used after every 3 passes]

Pass number from—	Average amount of metal removed per pass		Profilometer reading (rms microinches)		
	Ounces per strip	Equivalent thickness (×.000 01 in.)	Max	Min	Mean
4 to 6	0.39	31	41	30	36
16 to 18	.38	30	34	26	30
31 to 33	.39	31	37	25	31
43 to 45	.30	24	27	18	23

TABLE 4.—*Effect of pressure on polishing wheel with 90-grain head*

[Three passes per strip]

Polishing pressure	Total metal removed (×.000 01 in.)	Profilometer reading (rms microinches)			Unpolished area	
		Max	Min	Mean		
lb					*in.*^{2}	*Percent*
15	86	65	50	58	5	2
25	119	60	43	52	0.5	0.2
30	127	60	43	52	.5	.2
35	144	60	44	52	0	0
40	163	62	48	55	0	0

[a] Steel "burnt" on edges during polishing.

TABLE 5.—*Summary of polished-steel specimens*

Number	Grain size in final polish	Surface finish before final polish	Polishing pressure	Number of passes per strip	Average number of 6-ft strips per wheel head	Total metal removed (×0.000 01 inch)			Profilometer values (rms microinches)		
						Max	Min	Average per pass	Max	Min	Mean
			lb								
1	90	Cold-rolled	35	2	18	110	75	46	85	44	65
2	120	90-grain	30	2	11	78	69	37	42	39	41
3	150	Cold-rolled	25	3	7	108	83	32	37	26	32
4	150	90-grain	25	3	5	108	78	31	28	21	25
5	150	120-grain	25	3	5	94	86	30	29	23	26
6	180	150-grain	25	3	6	102	75	30	36	24	30
7	220	Cold-rolled	25	3	4	91	64	26	28	19	24
8	220	90-grain	25	3	4	89	61	25	28	19	24
9	220	150-grain	25	3	4	89	72	27	28	17	23
10	220	180-grain	25	3	4	86	55	24	24	21	23
11	320	Cold-rolled	25	3	2	72	39	19	19	12	16
12	320	220-grain	25	3	2+	61	30	15	17	10	14
13	Oiled 220	Dry 220-grain	45	3	6	22	11	6	16	12	14
14	Oiled 320	Dry 320-grain	40	3	3	19	11	5	11	6	9

TABLE 6.—*Summary of operations on the grease-polished specimens*

Operation number	Wheel head	Direction of polishing	Lubricant	Surface finish before final polish	Polishing pressure	Number of passes per strip	Total metal removed (×0.000 01 inch)			Average per pass	Profilometer value (rms microinches)		
							Max	Min	Average		Max	Min	Mean
					lb								
1	Rolled 220	Cross	None	Cold-rolled	25	3	83	72	78	26	22	14	18
2	do	Straight	Oil and kerosine	Dry 220	30	3	30	14	22	7	17	10	14
3	Paste 220	do	Tallow	Oiled 220	35	3	25	11	18	6	10	6	8
4	Paste 220, flint stoned	do	Tallow and charcoal	Grease 220	30	2	3	--------	--------	--------	9	5	7
				Total	--------	11	141	97	118	--------	--------	--------	--------

TABLE 7.—*Summary of operations on specimens finished with a "greaseless" aluminum-oxide compound*

Operation number	Surface finish	Previous surface finish	Polishing pressure	Number of passes per strip	Total metal removed (×0.000 01 inch)				Profilometer values (rms microinches)		
					Max	Min	Average	Average per pass	Max	Min	Mean
			lb								
1	Dry 220	Cold-rolled	25	3	94	72	83	28	26	21	24
2	Greaseless Al_2O_3, grade C.	Dry 220	35	2	6	3	4	2	22	16	19
		Total	--------	--------	100	75	87	--------	--------	--------	--------

TABLE 8.—*Electrolytic alkaline cleaning*

Cleaner	Base metal	Solution composition						Temperature	Current density	Time	
		Sodium hydroxide, NaOH	Sodium carbonate, Na_2CO_3	Trisodium phosphate, $Na_3PO_4.12H_2O$	Sodium pyrophosphate, $Na_4P_2O_7$	Sodium metasilicate, Na_2SiO_3	Sodium orthosilicate, Na_4SiO_4			Cathodic	Anodic
		oz/gal	*oz/gal*	*oz/gal*	*oz/gal*	*oz/gal*	*oz/gal*	°*F*	*amp/ft²*	*min*	*min*
N	Steel	0.5	4	4	--------	--------	--------	195	25	2	--------
N_1	Copper	.5	4	4	--------	--------	--------	195	25	1	--------
N_2	Steel	.5	4	4	--------	--------	--------	195	25	2	1
Chromium	Nickel	.5	2	2	--------	--------	--------	170	35	2	--------
H	Steel	2.0	--------	--------	--------	--------	5	195	25	2	1
H_1	Copper	2.0	--------	--------	--------	--------	5	195	25	1	--------
C	Steel	2.0	4	--------	2	0.5	--------	195	65	--------	1
C_1	do	2.0	4	--------	2	0.5	--------	195	25	2	1

TABLE 9.—*Pickling*

Base metal	Preparation for deposition of	Sulfuric acid, H_2SO_4, cp, 95%; sp gr 1.84	Hydrochloric acid, HCl, cp, 35%; sp gr 1.18	Temperature	Maximum time of immersion
		fl oz/gal	*fl oz/gal*	*°F*	*Seconds*
Cold-rolled steel	Dull nickel or copper	7		120	120
Polished steel	Dull nickel	7		120	15
Copperplated steel	Dull nickel or bright nickel	7		75	15
Cold-rolled and polished steel.	Bright nickel or copper		19	75	30
Buffed dull nickel on steel	Chromium	7		75	30
Bright nickel on steel	do		19	75	30

TABLE 10.—*Composition and operating conditions of Rochelle-salt copper-plating solution*

Composition	
Copper cyanide, CuCN, *oz/gal*	4.0
Total sodium cyanide, NaCN, *oz/gal*	5.0
Free sodium cyanide, NaCN, *oz/gal*	0.8
Sodium carbonate, Na_2CO_3, *oz/gal*	4.0
Rochelle salt, $NaKC_4H_4O_6.4H_2O$, *oz/gal*	6.0
Operating conditions	
pH (glass electrode, uncorrected)	11.0
Temperature, °F	150
Current density, amp/ft²	20

TABLE 11.—*Composition and operating conditions of dull-nickel-plating solution*

Composition	
Nickel sulfate, $NiSO_4.7H_2O$, *oz/gal*	27
Nickel chloride, $NiCl_2.6H_2O$, *oz/gal*	6
Boric acid, H_3BO_3, *oz/gal*	4
Operating conditions	
pH (quinhydrone) at 77° F	5.0
Temperature, *°F*	100
Current density, *amp/ft²*	19
Cathode bar oscillated.	

TABLE 12.—*Operating conditions of bright-nickel-plating solution*

pH (quinhydrone) at 77° F	3.0
Temperature, *°F*	128
Current density, *amp/ft²*	25
Cathode bar oscillated.	

TABLE 13.—*Composition and operating conditions of chromium-plating solution*

Composition	
Chromic acid, CrO_3 *oz/gal*	33
Sulfuric acid, H_2SO_4 *oz/gal*	0.33

Operating conditions		
Plating on—	Temperature	Current density
	°F	*amp/ft²*
Dull nickel	110	150
Bright nickel	110	175

TABLE 14.—*Summary of preparation and plating of steel specimens exposed in September 1941*

[B=bright nickel, S=dull nickel, +=buffed. 0.000 01 inch of chromium over nickel on all specimens]

4=4-inch steel originally supplied.
6=6-inch steel supplied later when 4-inch steel was used up.
N=Original cleaner, used with direct current only.
N_2=Original cleaner, used with direct and reverse current.
H=Harshaw cleaner, used with direct+reverse current.

Set number	Surface finish, abrasive grain size	Steel	Cleaning	Plating in 0.000 01 inch	
				Copper	Nickel
1	Cold-rolled	4	N	---	S 75
2	do	4	N	---	S 75+
2A	do	4	H	---	S 75+
3	do	6	H	---	B 75
3A	do	4	H	---	B 75
3B	do	6	N	---	B 75
4	do	6	H	---	B 40
4A	do	4	H	---	B 40
5	do	6	H	25+	B 50
5A	do	4	H	25+	B 50
5B	do	6	H	25	B 50
6	do	6	H	25+	B 100
6A	do	4	H	25+	B 100
7	90	4	N	---	S 75+
8	90	4	H	---	B 75
9	150	4	N	---	S 75
10	150	4	N	---	S 75+
11	150	4	H	---	B 75
12	150	4	H	---	B 40
13	150	4	H	25+	B 50
14	150	4	H	25+	B 100
15	90, 150	4	N	---	S 75+
16	90, 150	4	H	---	B 75
17	90, 150 cross	4	N	---	S 75+
18	90, 150 cross	4	H	---	B 75
19	90, 120, 150	4	N	---	S 75+
20	90, 120, 150	4	H	---	B 75
21	220	4	N	---	S 75
22	220	4	N	---	S 75+
23	220	4	H	---	B 75
24	220	4	H	---	B 40
25	220	4	H	25+	B 50
26	220	4	H	25+	B 100
27	220 oiled	4	N	---	S 75+
28	220 oiled	4	H	---	B 75
29	90, 220	4	N	---	S 75+

TABLE 14.—*Summary of preparation and plating of steel specimens exposed in September 1941*—Continued

Set number	Surface finish, abrasive grain size	Steel	Cleaning	Plating in 0.000 01 inch	
				Copper	Nickel
30	90, 220	4	H	--------	B 75
31	150, 220	4	N	--------	S 75+
32	150, 220	4	H	--------	B 75
33	150, 220 cross	4	N	--------	S 75+
34	150, 220 cross	4	H	--------	B 75
35	150, 180, 220	4	N	--------	S 75+
36	150, 180, 220	4	H	--------	B 75
37	320	4	N	--------	S 75+
38	320	4	H	--------	B 75
39	320 oiled	4	N	--------	S 75+
40	320 oiled	4	H	--------	B 75
41	220, 320	4	N	--------	S 75+
42	220, 320	4	H	--------	B 75
43	220, 320 cross	4	N	--------	S 75+
44	220, 320 cross	4	H	--------	B 75
45	Superfinished	4	N	--------	S 75+
46	do	4	H	--------	B 75
47	Cold-rolled	6	N_2	--------	S 75+
47A	do	4	N_2	--------	S 75+
48	do	6	N_2	--------	B 75

TABLE 15.—*Summary of preparation and plating of steel specimens exposed in April 1942*

[B=bright nickel, S=dull nickel, +=buffed. 0.000 01 inch of chromium over nickel on all specimens.]

4=4-inch steel originally supplied.
6=6-inch steel supplied later when 4-inch steel ran out.
N=Original project cleaner, used with direct current only.
H=Harshaw cleaner, used with direct+reverse current.
C=Low-silicate cleaner, used with reverse current only.
C_1=Low-silicate cleaner, used with direct and reverse current.

Set number	Surface finish abrasive grain size	Steel	Cleaning	Plating in 0.000 01 inch	
				Copper	Nickel
49	220 grease	6	N	--------	S 75+
50	do	6	H	--------	B 75+
51	Greaseless Al_2O_3	6	N	--------	S 75+
52	do	6	H	--------	B 75
53	Cold-rolled	6	N	--------	S 75+
53A	do	4	N	--------	S 75+
54	do	6	H	--------	B 75
54A	do	4	H	--------	B 75
55	do	6	N	25+	S 50+
56	do	6	N	50+	S 25+
57	do	6	H	50+	B 25
58	do	6	C	--------	S 75+
58A	do	6	C_1	--------	S 75+
59	do	6	C	--------	B 75
59A	do	6	C_1	--------	B 75
DUPLICATES OF ORIGINAL SETS EXPOSED IN APRIL 1942					
2	Cold-rolled	4	N	--------	S 75+
17	90, 150 cross	4	N	--------	S 75+
41	220, 320	4	N	--------	S 75+
3	Cold-rolled	6	H	--------	B 75
16	90, 150	4	H	--------	B 75
38	320	4	H	--------	B 75
5	Cold-rolled	6	H	25+	B 50

TABLE 16.—*Effect of surface finish on protective value of buffed dull-nickel plating on steel*

[0.000 75-inch final thickness of buffed dull nickel. 0.000 01 inch of chromium]

A. PANELS EXPOSED OCTOBER 1941

Set number	Surface finish	Outdoor exposure (*T*=total percentage score)								Accelerated tests (spots per specimen)			
		New York (57 weeks)		Sandy Hook (57 weeks)		Washington (61 weeks)		Average of 3 locations		Salt spray 100 hr	Condensation 240 hr	Ferroxyl 10 min	Hot water 6 hr
		T	Deviation from average	*T*	Deviation from average	*T*	Deviation from average	*T*	Deviation from average				
2	Cold-rolled	18	0	29	+2	85	−5	43	−2	1	0	1	1
7	90	20	+2	30	+3	93	+3	48	+3	40	0	4	1
10	150	18	0	25	−2	89	−1	44	−1	6	0	4	0
22	220	17	−1	23	−4	88	−2	43	−2	0	0	3	0
27	220 oiled	19	+1	29	+2	93	+3	47	+2	0	0	2	0
37	320	21	+3	20	−7	87	−3	43	−2	20	0	0	--------
39	320 oiled	19	+1	27	0	92	+2	46	+1	4	0	0	--------
45	Superfinished	18	0	32	+5	89	−1	46	+1	0	0	0	--------
	Average	18	±1	27	±3	90	±3	45	±2	--------	--------	--------	--------

B. PANELS EXPOSED APRIL 1942

Set number	Surface finish	Steel width	Prepared	Outdoor exposure (T=total percentage score)							
				New York (31 weeks)		Sandy Hook (31 weeks)		Washington (32 weeks)		Average of 3 locations	
				T	Deviation from average	T	Deviation from average	T	Deviation from average	T	Deviation from average
		Inches									
49	220 grease	6	1942	60	+5	64	+7	90	−2	71	+3
51	Greaseless Al_2O_3	6		52	−3	60	+3	87	−5	66	−2
53	Cold-rolled	6		54	−1	48	−9	94	+2	65	−3
53A	do	4		52	−3	57	0	96	+4	69	+1
	Average			55	±3	57	±5	92	±3	68	±2
2	Cold-rolled	4	1941	43	−3	49	+10	90	−2	61	+2
17	90, 150 cross	4		45	−1	32	−7	91	−1	56	−3
41	220, 320	4		51	+5	37	−2	96	+4	61	+2
	Average			46	±3	39	±6	92	±2	59	±2

TABLE 17.—*Effect of surface finish on protective value of bright-nickel plating on steel*

[0.000 75 inch of bright nickel. 0.000 01 inch of chromium]

A. EXPOSED OCTOBER 1941

Set number	Surface finish	Outdoor exposure (T=total percentage score)								Accelerated tests (spots per specimen)			
		New York (57 weeks)		Sandy Hook (57 weeks)		Washington (61 weeks)		Average of 3 locations		Salt spray 100 hr	Condensation 240 hr	Ferroxyl 10 min	Hot water 6 hr
		T	Deviation from average	T	Deviation from average	T	Deviation from average	T	Deviation from average				
3A	Cold-rolled	20	−1	15	+4	52	+5	29	+2	3	9	0	5
8	90	24	+3	12	+1	47	0	28	+1	3	7	0	0
11	150	18	−3	10	−1	47	0	25	−2	1	1	1	0
23	220	19	−2	10	−1	46	−1	25	−2	3	8	0	1
28	220 oiled	27	+6	9	−2	56	+9	31	+4	30	9	1 to 9	1
38	320	18	−3	8	−3	42	−5	23	−4	2	6	1	0 to 15
40	320 oiled	28	+7	13	+2	49	+2	30	+3	4	2	1	---------
46	Superfinished	16	−5	12	+1	38	−9	22	−5	3	1	0	---------
	Average	21	±4	11	±2	47	±4	27	±3	---------	---------	---------	---------

B. PANELS EXPOSED APRIL 1942

Set number	Surface finish	Steel width	Pre-pared	Outdoor exposure (*T*=total percentage score)							
				New York (31 weeks)		Sandy Hook (31 weeks)		Washington (32 weeks)		Average of 3 locations	
				T	Deviation from average	*T*	Deviation from average	*T*	Deviation from average	*T*	Deviation from average
		Inches									
50	220 grease	6	1942	70	+5	39	+7	56	−1	55	+3
52	Greasless Al_2O_3	6		55	−10	26	−6	54	−3	45	−7
54	Cold-rolled	6		68	+3	25	−7	54	−3	49	−3
54A	do	4		68	+3	39	+9	63	+6	57	+5
	Average			65	±5	32	±7	57	±3	52	±5
3	Cold-rolled	6	1941	45	−2	23	0	57	+11	42	−3
16	90, 150	4		43	−4	23	0	37	−9	34	−5
38	320	4		54	+7	23	0	44	−2	40	+1
	Average			47	±4	23	0	46	±6	39	±3

TABLE 18.—*Effect of polishing depth on protective value of buffed dull-nickel plating on steel*

[0.000 75 inch of buffed dull nickel. 0.000 01 inch of chromium. Panels exposed October 1941]

Set number	Polishing operations	Total metal removed by polishing operations (×0.000 01 in.)	Outdoor exposure (*T*=total percentage score)							
			New York (57 weeks)		Sandy Hook (57 weeks)		Washington (61 weeks)		Average of 3 locations	
			T	Deviation from average	*T*	Deviation from average	*T*	Deviation from average	*T*	Deviation from average
10	150	96	18	0	25	+1	89	−2	44	−1
15	90, 150	186	20	+2	31	+5	91	+1	48	+3
17	90, 150 cross	194	17	−3	18	−8	87	−3	41	−4
19	90, 120, 150	257	19	+1	28	+2	92	+2	46	+1
	Average		18	±2	26	±4	90	±2	45	±2
22	220	78	17	−1	23	−1	88	−3	43	−1
29	90, 220	168	23	+5	24	0	89	0	45	+1
31	150, 220	177	15	−3	24	0	92	+2	44	0
33	150, 220 cross	177	18	0	27	+3	91	+3	45	+1
35	150, 180, 220	256	19	+1	22	−2	90	0	44	0
	Average		18	±2	24	±1	90	±2	44	±1
37	320	56	21	+2	20	−3	87	−3	43	−1
41	220, 320	124	21	+2	25	+2	93	+2	46	+2
43	220, 320 cross	124	16	−3	24	+1	92	0	44	0
	Average		19	±2	23	±2	91	±2	44	±1

TABLE 19.—*Effect of polishing depth on protective value of bright-nickel plating on steel*

[0.000 75 inch of bright nickel. 0.000 01 inch of chromium. Panels exposed October 1941]

Set number	Average metal removed by polishing operations (×0.000 01 in.)	Surface finish	Outdoor exposure (*T*=total percentage score)							
			New York (57 weeks)		Sendy Hook (57 weeks)		Washington (61 weeks)		Average of 3 locations	
			T	Deviation from average	*T*	Deviation from average	*T*	Deviation from average	*T*	Deviation from average
11	96	150	18	0	10	−1	47	+1	25	0
16	186	90, 150	19	+1	10	−1	44	−2	24	−1
18	194	90, 150 cross	15	3	8	−3	43	−3	22	−3
20	257	90, 120, 150	20	+2	14	+3	48	+2	27	+2
		Average	18	±2	11	±2	46	±2	25	±2
23	78	220	19	−3	10	0	46	+1	25	−1
30	168	90, 220	26	+4	11	+1	46	+1	28	+2
32	177	150, 220	27	+5	9	−1	47	+2	28	+2
34	177	150, 220 cross	23	+1	13	+3	46	+1	27	+1
36	256	150, 180, 220	15	−7	8	−2	38	−7	20	−6
		Average	22	±4	10	±1	45	±2	26	±2
38	56	320	18	−6	8	−1	42	−3	23	−3
42	124	220, 320	28	+4	11	+2	49	+4	29	+3
44	124	220, 320 cross	26	+2	9	0	44	−1	26	0
		Average	24	±4	9	±1	45	±2	26	±2

TABLE 20.—*Effect of buffing on protective value of dull-nickel plating on steel*

[0.000 01 inch of chromium over nickel. Panels exposed October 1941.]

Set number	Surface finish	Nickel plating	Outdoor exposure (T=total percentage score)							
			New York (57 weeks)		Sandy Hook (57 weeks)		Washington (61 weeks)		Average of 3 locations	
			T	Deviation from average	T	Deviation from average	T	Deviation from average	T	Deviation from average
1	Cold-rolled	S 75	47	+23	75	+35	94	+4	72	+21
2	do	S 75+	18	−6	29	−11	85	−5	44	−7
9	150	S 75	19	−5	45	+5	91	+1	52	+1
10	150	S 75+	18	−6	25	−15	89	−1	44	−7
21	220	S 75	26	+2	39	−1	94	+4	53	+2
22	220	S 75+	17	−7	23	−17	88	−2	43	−8
	Average of all		24		40		90		51	
	Average unbuffed nickel.		31		53		93		59	
	Average buffed nickel.		18		26		87		44	

TABLE 21.—*Effect of variations in cleaning on protective value of nickel plating on steel*

[0.000 75 inch final thickness of buffed dull- or bright-nickel, 0.000 01 inch of chromium. All steel, except 2*, 4 inch, was cold-rolled 6-inch stock. Panels exposed April 1942.]

Set number	Cleaning	Plating	Outdoor exposure (T=total percentage score)							
			New York (31 weeks)		Sandy Hook (31 weeks)		Washington (32 weeks)		Average of 3 locations	
			T	Deviation from average	T	Deviation from average	T	Deviation from average	T	Deviation from average
53	N	S 75+	54	+2	48	−1	94	0	65	0
58	C	S 75+	56	+4	46	−3	96	+2	66	+1
58A	C_1	S 75+	56	+4	51	+2	95	+1	68	+3
2*	N	S 75+	43	−9	49	0	90	−4	61	−4
	Average, dull-nickel.		52	±5	49	±2	94	±2	65	±2
54	H	B 75	68	+6	25	−4	54	−2	49	0
59	C	B 75	67	+5	34	+5	54	−2	52	+3
59A	C_1	B 75	68	+6	34	+5	59	+3	54	5
3	H	B 75	45	−17	23	−6	57	+1	42	−7
	Average, bright-nickel.		62	±8	29	±5	56	±1	49	±4

TABLE 22.—*Effect of surface finish on protective value of various thicknesses of nickel with and without copper undercoat*

[0.000 01 inch of chromium]

Set number	Surface finish	Plating	Outdoor exposure (*T*=total percentage score)							
			New York (57 weeks)		Sandy Hook (57 weeks)		Washington (61 weeks)		Average of 3 locations	
			T	Deviation from average	*T*	Deviation from average	*T*	Deviation from average	*T*	Deviation from average
			A. EXPOSED OCTOBER 1941							
4A	Cold-rolled	B 40	15	−1	9	+1	35	−1	20	−1
12	150	B 40	19	+3	8	0	38	+2	16	+1
24	220	B 40	15	−1	7	−1	39	−2	14	−1
Average			16	±2	8	±1	36	±2	15	±1
3A	Cold-rolled	B 75	20	+1	15	+3	52	+4	29	+3
11	150	B 75	18	−1	10	−2	47	−1	25	−1
23	220	B 75	19	0	10	−2	46	−2	25	−1
Average			19	±1	12	±2	48	±2	26	±2
5A	Cold-rolled	Cu 25+, B 50	24	−3	33	+3	83	+1	47	0
13	150	Cu 25+, B 50	28	+1	27	−3	77	−5	44	−3
25	220	Cu 25+, B 50	30	+3	30	0	86	+4	49	+2
Average			27	±2	30	±2	82	±3	47	±2
6A	Cold-rolled	Cu 25+, B 100	50	+5	65	0	90	−2	68	0
14	150	Cu 25+, B 100	46	−1	64	−1	95	+2	68	0
26	220	Cu 25+, B 100	40	−5	67	+2	93	0	67	−1
Average			45	±4	65	±1	93	±2	68	±1

B. PANELS EXPOSED APRIL 1942

Set number	Plating		Outdoor exposure (*T*=total percentage score)							
	Copper	Nickel	New York (31 weeks)		Sandy Hook (31 weeks)		Washington (32 weeks)		Average of 3 locations	
			T	Deviation from average	*T*	Deviation from average	*T*	Deviation from average	*T*	Deviation from average
53		S 75+	54	+3	48	−8	94	−1	65	−2
55	25+	S 50+	55	+4	60	+4	99	+4	71	+4
56	50+	S 25+	43	−8	60	+4	92	−3	65	−2
Average, dull nickel			51	±5	56	±5	95	±3	67	±3
54		B 75	68	+10	25	−14	54	−16	49	−7
57	50+	B 25	64	+6	55	+16	86	+16	68	+12
3		B 75	45	−13	23	−16	57	−13	42	−14
5	25+	B 50	56	−2	54	+15	82	+12	64	+8
Average, bright nickel			58	±8	39	±16	70	±14	56	±10

WASHINGTON, January 5, 1945.