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THE CAUSES FOR POROSITY AND LEAKAGE IN NON-FERROUS CASTINGS (THE EFFECT OF REPLACING TIN BY NICKEL ON THE POROSITY, MECHANICAL PROPERTIES AND CORROSION RESISTANCE OF TIN BRONZE)

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ABSTRACT

Replacing tin by nickel in composition G improves porosity and does not impair mechanical properties. The corrosion rate in quiescent Severn River water is not affected by changes in composition, but in high velocity water it increases as tin is replaced by nickel.

The mechanical properties of composition M and red brass are not impaired by replacing tin by nickel, but no marked improvement in porosity was noted. Composition governs the corrosion rate in high velocity water and does not influence it in quiescent water.

In the addenda methane is shown to be a source of porosity in bronze, and the corrosion rate of various standard and modified bronze compositions in sea water at Wilmington, North Carolina after one year's exposure was shown to be approximately the same. A complete record of corrosion tests completed and in progress is incorporated in six tables.

AUTHORIZATION

1. The study on non-ferrous castings was authorized by Bureau of Engineering Project Order No. 140/39 dated 23 November 1938, which read as follows: "Study the causes and devise remedies for porosity and leakage in non-ferrous castings".

2. Evidence was presented in NRL report M-1650 dated 29 August 1940 to show that the substitution of nickel for tin in composition G tended to reduce intercrystalline shrinkage. Accordingly, authorization to determine the possibilities of replacing tin by nickel in compositions G, M and S-c and red brass was granted in Bureau of Ships letter (QP/Castings (DYs-2)) to NRL, 23 January 1941.

3. Authority to perform sea water corrosion tests at Annapolis, Maryland and Wilmington, North Carolina was given the Naval Engineering Experiment Station and The International Nickel Company, respectively in the following letters: Bureau Ships to Director, EES (QP/Castings (DYs-Dw)) dated 5 May 1941, Bureau of Ships to Director, NRL, (JJ46-10 (3692)) dated 10 May 1941, and Bureau of Ships to Director, NRL (JJ46-(9)(354)), dated 13 May 1942.

4. The Naval Research Laboratory prepared all specimens and selected most of the alloys. The remaining alloys were recommended by representatives of the Bureau of Ships and The International Nickel Company. A record of the corrosion studies completed and in progress is included in the appendix.

STATEMENT OF PROBLEM

5. It has been shown that intercrystalline shrinkage porosity was considerably reduced when 6 percent nickel replaced 6 percent tin in composition G(1). This was considered to be extremely important in connection with the manufacture of bronze castings which are required to withstand hydrostatic pressure, because it was felt that the number of rejections due to leakage would be reduced. Although nickel bronzes were then used to a limited extent commercially, not too much was known about their internal soundness, or about their mechanical properties and sea water corrosion resistance, all of which must be considered in the choice of material for many marine applications. Therefore, a systematic investigation was undertaken to determine the effect of replacing various amounts of tin by nickel on these properties of compositions G and M and red brass.

6. The purpose of this report is (1) to present

evidence on the effect of replacing tin by nickel on porosity, tensile properties and sea water corrosion resistance of composition G and M, and red brass, (2) to outline the status of sea water corrosion testing completed and in progress both at the Naval Engineering Experiment Station, Annapolis, Maryland and at The International Nickel Company test racks, Dow Chemical Company, Wilmington, North Carolina, and (3) to outline research planned and in progress at this laboratory.

KNOWN FACTS AND THEORETICAL CONSIDERATIONS

7. Leakage or the lack of pressure-tightness has been attributed to porosity of which there are two general types, intercrystalline shrinkage and gas porosity. Leakage has also been attributed to such defects as cracks, cold shuts and sand inclusions. Gas and intercrystalline shrinkage porosity are rather difficult to eliminate.

(a) Gas Porosity

8. Gas porosity in general may be a result of (1) the precipitation of gases soluble in the liquid state but practically insoluble in the solid state, (2) the entrapment of insoluble mold gases while casting and during solidification, and (3) the reduction of metallic oxides while casting to form carbon monoxide and carbon dioxide which may ultimately be entrapped. Gas porosity takes the form of spheres in which the metal in direct contact with the gas remains bright and clean, and is generally scattered throughout the sections or is segregated at the metal surface, or both. Unless convenient channels exist between gas pockets from metal surface to surface or unless there are channels extending from surface to surface on gas free castings, leakage would not be expected when the casting is subjected to hydrostatic pressure.

(b) Intercrystalline Shrinkage Porosity

9. Intercrystalline shrinkage cavities, generally tetrahedral in shape under the microscope, are located at dendrite interfaces. They are formed even under carefully controlled laboratory conditions when melting and solidifying in vacuo(1) thereby negating the possibility of this type of porosity being due to precipitated or entrapped gases. In view of this fact, one logical explanation for the cause of intercrystalline shrinkage porosity is based on the wide freezing range of copper-tin alloys containing approximately 9 percent tin. Slow or prolonged freezing generally occurs in sand castings. Thus, with a wide cooling range a considerable depth of metal from the cooling face of the casting will be freezing at the same time and the feeding

liquid must traverse a long network of dendrites to fill the cavities. Since the cavities are not formed as a result of precipitated or entrapped gases, only one other possibility exists to which their formation can be attributed, namely contraction.

10. The amount of intercrystalline shrinkage porosity can be controlled by controlling the rate of solidification, i.e. if the casting temperature is above normal, the contraction during solidification will be greater than if cast at a normal temperature. Tin bronzes produce the fewest intercrystalline shrinkage cavities when they are poured at temperatures as low as it is practicable to insure good mold reproduction and to avoid cold shuts. However, the tin bronze sand castings cannot be produced entirely free from contraction cavities even when the most favorable casting temperatures are employed which is evidenced by the fact that maximum densities for given compositions are not obtained. (Compare Plates 1 and 2). It may be that the highest density obtainable at normal pouring temperatures is sufficient to produce pressure-tight castings but it is possible to obtain this density within a limited pouring range only; too low a pouring temperature results in such defects as cold shuts, inclusions and poor mold reproduction while too high a pouring temperature results in many internal cavities. Complicated castings are poured at temperatures which are determined by the thinnest section. The pouring temperature may be much too high for the heavy sections and an excessive cavity formation will result in the heavy sections. Chilling the heavy section will help, but the pouring temperature of these alloys must be held within narrow limits. When 6 percent tin is replaced by 6 percent nickel in composition G, maximum cast density may be obtained over a wide pouring range. Thus, a sensitive casting alloy is converted to a more flexible foundry composition. Two distinct advantages are immediately gained: (1) pouring temperature is no longer critical, and (2) the rate of solidification in castings having both heavy and light sections is also less critical so long as the principles of directional solidification are followed.

(c) Reproducibility of results

11. The many variables encountered in the foundry make results difficult to reproduce. In producing large numbers of castings a certain percentage is always rejected due to porosity, low mechanical properties, cold shuts, poor mold reproduction, leakage, or other defects. Even if the molding practice, melting technique and alloy content are carefully controlled from one heat to another, variations in density and mechanical properties occur. By

averaging the results of a number of tests, trends become apparent which are often misleading, particularly in casting studies, unless the standard deviations from the mean are considered.

12. For example, suppose that it is desired to determine how the porosity of a bronze is affected by variations in pouring temperature. After data from several heats have been accumulated, the variations in density for the different pouring temperatures are averaged arithmetically. An average density-pouring temperature curve may then show that porosity increases very little with increases in pouring temperature, while the standard deviations from the mean densities may be narrow at low pouring temperatures and wide at high pouring temperatures. Thus, the mean density-pouring temperature curve of an alloy may show desirable characteristics although the standard deviations may indicate that the density becomes critical at high pouring temperatures, for example, plate 3, density-pouring temperature curve for G*.

EXPERIMENTAL PROCEDURE

(a) Compositions Used

13. Since the replacement of 6 percent of the tin by nickel in composition G was found to produce an alloy which gave lower porosity over a wide pouring temperature range, a study of its corrosion resistance and that of other nickel bearing bronzes was undertaken. Heats of composition G were made in which 3, 6, 7.5 and 9 percent of its nominal 9 percent tin were replaced by the same weight percent of nickel. The effect of nickel on composition M and red brass also was studied. The effect of pouring temperature on porosity, tensile properties and fluidity was determined as well as the effect of composition on the corrosion resistance to Severn River water.

(b) Porosity. Mechanical Properties and Fluidity

Foundry technique:

14. Melting charges consisted of the highest quality virgin metals, selected Naval Research Laboratory Foundry scrap of known composition and a master alloy of copper-nickel for nickel additions. Several heats were made of virgin metals alone while the others were prepared from scrap and virgin metals. The properties of the virgin metal heats were approximately the same as those of the heats made from virgin metals and scrap. General foundry practice was simulated by using charges consisting

of both virgin metals and selected scrap.

15. All charges for castings to be used for the determination of density and tensile properties were melted in a 210 pound capacity lift coil type, high frequency induction furnace. Charges for corrosion specimens and fluidity spirals were melted either in the induction furnace, or in a 120 pound capacity stationary, crucible type, oil fired furnace depending upon the size of the charge. The oil fired furnace was operated with a slightly oxidizing atmosphere, while no attempt was made to control the atmosphere in the high frequency furnace except by means of the usual charcoal cover. Clay-graphite crucibles were used in both furnaces.

16. Virgin copper, selected scrap and the copper-nickel master alloy (when required) were melted together. Tin was added to the molten metal (if necessary) and sufficient zinc was added to balance the composition and compensate for melting losses. The melts were stirred a few minutes before pouring the first mold. The metal was heated to approximately 1300°C (2372°F) when the crucible was removed from the furnace. After skimming, the metal was poured into three molds at 1250°C (2282°F), 1150°C (2102°F) and 1050°C (1922°F), respectively.

17. Match plate patterns were used for the molds which were made of Albany green sand (Grade 00) or its equivalent containing from 6 to 8 percent moisture. The molds were allowed to air dry at least 24 hours before casting. The standard bronze test casting(3) (Fig. 10A, Plate 9) was used extensively for all compositions so that the tests would be comparable to accepted foundry practice. Because of its rather complicated design, the standard aluminum test casting,(3) (Fig. 11A, Plate 9) was also used for tests on composition G, G-1, and G-2. An asterisk affixed to the composition letter signifies that type 11A mold was used, e.g. G*, G-1*, G-2*. Since type 10A test casting shows merely the properties of the metal, type 11A test casting was used in addition because it gives properties more representative of those in a complicated casting. In order to avoid possible variations, the same melting, molding and casting techniques were employed for each heat.

Fluidity tests:

18. The running characteristics of the basic compositions were compared with those of the modified compositions by means of the Naval Research Laboratory fluidity test(2). The fluidity curves were obtained by plotting spiral lengths in inches versus pouring temperature.

Five different pouring temperatures between 1100°C (2012° F) and 1300°C (2372°F) were selected, and enough different heats (a minimum of four) were run to establish an average curve for each composition. Fluidity spirals were poured when the desired pouring temperatures were reached on cooling.

Density determination:

19. "As cast" density of both rough tensile specimens from each mold was determined by the conventional displacement of water method and standard 0.505 inch threaded end tensile specimens were used. Maximum density values (Table I, Plate I) were determined by x-ray diffraction with a back reflection camera. To insure internal soundness and homogeneity one inch cubes of the "as cast" alloys were reduced 75 percent by cold compressing and annealing. These specimens were then trimmed to 1/4 inch by 1 inch by 1 inch coupons, polished and etched before exposure.

Compilation of data:

20. In order to determine the effect of pouring temperature on density, tensile strength and elongation, several heats were run for each composition (Tables II and III). Standard deviations (4) were calculated after the mean values had been computed. The cross-hatched areas in Plates 2, 3, 4 and 5, within which 68 percent of the observations fall, show the standard deviation from the mean curve which is the heavy line drawn through the center of each area.

(c) Resistance to Corrosion

21. Compositions G and M and red brass are well known for their excellent resistance to sea water corrosion. Therefore, when a change in composition to improve internal soundness is considered, it is necessary to determine what effect the changes will have on sea water corrosion resistance as well as on mechanical properties.

22. Accordingly, a series of alloys was tested for resistance to corrosion in the brackish water of the Severn River, at the U. S. Naval Engineering Experiment Station, Annapolis, Maryland.

23. The composition of a one-gallon sample of water taken during the summer months is given in Table IV, and except for temporary dilution due to unusually heavy

rainfall or spring thaw, can be accepted as typical.

24. The ratio, epm. Mg^{++}/epm. Ca^{++}, is 4.83 for the Severn River water and 4.60 for sea water, indicating that these waters differ in concentration rather than constituents.

25. The test specimens were rectangular plates and hollow cylinders with finely machined surfaces and were completely submerged in water in wooden tanks or earthenware crocks of large capacity during the tests. Water pumped directly from the river to a large gravity tank flowed continuously to these containers. An auxiliary source of supply was available to avoid shut-downs due to pump failure or necessary overhaul. A semi-automatic, thermostatically controlled steam heater maintained the temperature of the water between 75 and 85 degrees F.

26. The rectangular specimens were tested at zero velocity and at 30 ft. per second; the cylindrical specimens were tested at 15 ft. per second. A velocity of 30 ft. per second is higher than normally encountered. The modified composition G alloy containing 6 percent nickel was tested in the "as cast", the "aged" and the "annealed" conditions. The heat treatments were as follows: the "aged" samples were water quenched after 6 hours at 1400°F and aged 6 days at 700°F; the "annealed" samples were furnace cooled after 6 hours at 1400°F. All other alloys were in the "as cast" condition.

Preparation of Test Specimens:

27. The specimens for the tests were cut from plates and hollow cylinders cast in green sand molds. The plates were 6 inches long by 4 inches wide by 1 inch thick, and the cylinders were 20 inches long by 2-3/8 inches outside diameter by 1 inch inside diameter. Strips cut from the plates were machined to 1/4 inch thick by 15/ 16 inch wide. Three specimens of each alloy were prepared from the plates; two were 6 inches long and one was 4 inches long. Holes were drilled at one end of these specimens for fastening in the corrosion apparatus. Specimens from the cylinders were machined to 2-5/16 inches outside diameter, 1-1/2 inches inside diameter, 1-1/4 inches long.

Method of Test:

28. Two specimens, 6 inches long by 15/16 inch wide, of each alloy, spaced 3/4 inch apart, were suspended from glass rods in a large wooden tank of slowly moving Severn River water. The test pieces, which were motionless

during the test, were removed from the tank after 40, 80 and 125 days, scrubbed with a bristle brush under tap water, dried and weighed.

29. Specimens, 4 inches long by 15/16 inch wide, were bolted at 30 degree intervals on both sides of a micarta wheel 12 inches in diameter by 1/2 inch thick. The specimens on one side of the wheel were directly opposite those on the other side and projected 2 inches beyond the circumference of the wheel. The test pieces were held in place with 1/4 inch bolts and pins, one bolt and pin holding two specimens. The pins were made of hard rubber and the bolts were positively insulated from the specimens with a combined bushing and washer of micarta for each specimen.

30. The wheel was securely fastened to the center section of a horizontal monel metal line shaft which passed through a covered wooden tank fitted with stuffing-boxes. The section of shaft holding the wheel and specimens could be removed by means of flange couplings.

31. The shaft was revolved between 385 and 420 rpm. At this speed, the velocity of the projecting ends of the specimens was between 28 and 31 ft. per second. Only one specimen of each alloy was tested, as space was not available for duplicate samples.

32. The specimens were removed from the wheel after 28 and 69 days, scrubbed with a bristle brush in tap water, dried and weighed.

33. Four cylindrical specimens were assembled into pipes with a micarta ring between adjacent specimens and at each end of the column. Each column of specimens was held concentrically on the reduced section of a monel metal shaft 1-1/4 inches in diameter by 12 inches long. Pressure from a nut at one end of the shaft forced the column against a shoulder and held the specimens tightly together. The micarta rings insulated the specimens from one another and from the shaft. Ordinary rubber bands were successfully used between the specimens and rings to obtain a water-tight joint.

34. Each shaft of four specimens was screwed onto the shaft of a vertically mounted motor and revolved at 1500 rpm. At this speed, the surface velocity of the specimens was approximately 15 ft. per second. After 28 days the specimens were removed, washed off under tap water, dried and weighed.

DISCUSSION OF RESULTS

(a) Porosity

35. Since the density of a porous casting is less than the density of a non-porous casting, the degree of porosity may be estimated by a comparison of the densities of the alloy cast under different conditions or with its maximum density. To determine the maximum density of some alloys it is necessary to resort to the procedure employed on the G series, (Table I and Plate 1). The change in maximum density resulting from the replacement of tin by nickel is surprisingly small in view of the difference in density of these elements. A comparison of the maximum densities determined by x-ray methods with the densities of the cast alloys indicates a porosity of about one percent for G, G-1 and G-2, even under the most favorable conditions.

36. A suitable alloy for the foundry would be one that could be produced consistently free of porosity, even when subjected to variations in pouring temperature or adverse conditions which frequently occur in the foundry from day to day. Since density is a measure of porosity, an increase in "as cast" density or the maintenance of a constant and high "as cast" density over a wide pouring temperature range should represent a potential reduction in the number of castings rejected due to leakage. Therefore, if the density remains unchanged and can be reproduced within very narrow limits (narrow standard deviations) when subjected to variations in pouring temperature a definite improvement in soundness characteristics has been attained. Plates 2 and 3 show the effect of replacing tin by nickel in composition G, Plate 4 shows the effect of nickel on composition M, Plate 5 shows the possible influence on red brass, and Plate 6 is a composite of the mean (average) curves for data recorded on Plates 2, 4 and 5.

37. If the density can be held constant over a wide pouring temperature range and the sea water corrosion resistance maintained, it is necessary for the alloy to meet only the mechanical requirements of the basic composition in order to be a satisfactory replacement. In Plate 2 (10A test mold) a constant high density is maintained by alloy G-2 within very narrow limits over a wide pouring temperature range, while in Plate 3 (11A test mold) the same trends are shown for alloys G-1* and G-2*. Although the trends of the mean curves for composition G are similar, a striking difference in the standard deviations of the density-

pouring temperature curves exists between Plates 2 and 3. (If the suggestion is true that type 11A test casting may give a more representative picture of the properties of complicated castings, the soundness will be very inconsistent from casting to casting and from day to day). The density-pouring temperature data from types 10A and 11A test castings check very well for composition G-2, and this alloy seems to be desirable from the standpoint of soundness. In Plate 4 compositions M, M-1 and M-2 show a decrease in density with an increase in pouring temperature. The curves are similar to, but steeper than, those for composition G. The replacement of tin by nickel (M-1) decreases the standard deviation and moves the mean curve a little upward but does not affect the slope of the mean curve. The substitution of nickel for copper (M-2) moves the mean curve upward but does not affect its slope. The standard deviation is about the same as it is for composition M. In Plate 5 even though only three heats were run on red brass the trends are indicated. Only one heat of R.B.-1 was run because the resistance to corrosion of the alloy in Severn River water did not compare favorably with the resistance to corrosion of the basic compostion. There is no indication that the replacement of tin by nickel will produce the same results as obtained in the G series, although it is likely that the mean curve would have moved upward. By comparing the mean density-pouring temperature curves (Plate 6) of the basic compositions, G and M and red brass, it may be seen that as the lead content increases from 0 percent in composition G to 5 percent in red brass, the density which remains constant with variations in pouring temperature for composition G becomes critical to pouring temperature for composition M and red brass.

38. In Table III the density of the 7.5 percent and 9 percent nickel bronzes remained constant when the pouring temperature was varied. However, in view of the poor sea water corrosion resistance and low tensile strength of these alloys, work was discontinued.

(b) Mechanical Properties

39. Having shown a means by which internal soundness may be improved, the next question is, can the modified compositions meet the minimum mechanical requirements listed below for compositions G, M and red brass?

	Tensile Strength P.S.I.	Elongation Percent in two inches
Composition G	40,000	20
Composition M	34,000	22
Red Brass	30,000	20

In Plate 6 the mean tensile strength- and elongation-pouring temperature curves show that these requirements can be met. Plates 2 and 4 show the standard deviations for composition G and M and their modifications. In Plate 2 the tensile strength of composition G-2 is a little lower than compositions G and G-1, however the standard deviations for G-1 and G-2 are much smaller than for G. The elongation of composition G-2 is also lower, but again the standard deviation is much smaller than for both G and G-1. Although the progressive replacement of tin by nickel results in less variation in properties, the mechanical properties of the alloys seem to be lowered somewhat. The mechanical properties of composition M are not lowered when tin is replaced by nickel (Plate4). The tensile strength of M-1 and M-2 and the elongation of M-2 are very much more stabilized. Plate 5 shows that the mechanical properties of one heat of R.B.-1 were a little higher than the basic composition (R.B.) and that the same trends with pouring temperature are probable.

40. In Plate 3,11A test mold, a non-standard type for bronze, was used. Pouring temperature has less effect on the mechanical properties than appeared from the smaller amount of data reported earlier(1). Additional data show that the mechanical properties are less sensitive to pouring temperature, but the average values of 11A test mold data when compared with 10A test mold data are somewhat lower than the minimum requirements,particularly at the low temperature end of the pouring range. In spite of the low mechanical properties, the densities of G-1* and G-2* are still satisfactory, while G* shows a very wide standard deviation. Though the mechanical properties fall below the minimum requirements when tested under non-standard conditions, compositions G-1* and G-2* are equal to, or superior to composition G*.

(c) Fluidity

41. The replacement of 6 percent tin by 6 percent nickel in composition G markedly lowers the fluidity, (Plate 7, curve G-2). Likewise, the replacement of 2.5 percent tin by 2.5 percent nickel in red brass lowers

the fluidity somewhat, (curve R.B.-1). Other additions or replacements of tin by nickel in bronze have no marked influence on fluidity. It follows that for compositions G-2 and R.B.-1 a pouring temperature higher than normal for the basic compositions is required.

(d) Microstructure

42. Several pieces of each composition, cut from the ends of the tensile bars before pulling, were examined microscopically (Plate 8). All compositions except G-2 showed the typical cored structure with intercrystalline shrinkage cavities at the dendrite interfaces. G-2 showed no evidence of coring and there was a marked lack of intercrystalline shrinkage porosity. This further substantiates its high "as cast" density.

(e) General

43. Complicated castings have been satisfactorily made from composition G-2 in the foundry of the Naval Research Laboratory and elsewhere. It has been reported to be a more satisfactory alloy than composition G for the manufacture of pressure-tight castings. Standard tin bronze molding practice has been found suitable, with pattern shrinkage, and gating and risering methods virtually the same. No composition shown in Table II appeared to be subject to gas porosity except G-2 which was found to occasionally contain sub-surface pin hole gas porosity. Best results were obtained, however, with this composition by melting without a cover under slightly oxidizing conditions in an oil fired furnace. The gas porosity seemed to be associated with melting under a charcoal cover or in the high frequency induction furnace or both,

(f) Resistance to Corrosion

Motionless rectangular specimens;

44. The results of this test are shown graphically in Plate 10. The corrosion rate is expressed in milligrams per square inch per day. The open and the two hatched columns represent the successive test periods of 40, 80 and 125 days, respectively. The progressive replacement of tin by nickel produced no definite change in the corrosion rate of the composition G and M in quiescent Severn River water. Heat-treatment had little effect on the corrosion rate of the 6 percent nickel, 3 percent tin alloy (G-2). A definite but small increase

in the corrosion rate of the 85-5-5-5 alloy was produced by the substitution of 2.5 percent nickel for an equal quantity of tin.

45. The character of the corrosion product which formed on these specimens is closely related to the composition of the alloy. Specimens of the regular compositions, that is, those containing no nickel, were covered with a thin, tenacious and protective film. As the tin content of the alloys was decreased and replaced by the equivalent in nickel, the corrosion film changed to a thin scale of low tenacity. The corrosion product was completely and easily removed from the one "tin-free" 9 percent nickel alloy of the composition G group.

Rotating rectangular specimens:

46. The results of this test are shown graphically in Plate II. The corrosion rate is expressed in milligrams per square inch per day. The open and the solid columns represent the successive test periods of 28 and 69 days, respectively.

47. The corrosion rate of composition G increased gradually as the tin content of the alloy was decreased and replaced by nickel up to 4 percent. When the tin content became less than 6 percent, the corrosion rate increased rapidly. The corrosion rate of the alloy containing 6 percent nickel and 3 percent tin (G-2) was not appreciably decreased by heat treatment.

48. The substitution of 1 percent nickel for 1 percent tin in composition M (M-1)had little effect on the corrosion rate, but when the tin content was reduced to 3.5 percent by substitution of nickel, the corrosion rate was increased about nine times. The corrosion rate of the red brass alloy containing 2.5 percent nickel and 2.5 percent tin (R.B.-1)was several times greater than that of the standard composition.

49. The appearance of the test specimens was an excellent index to their corrosion rates. The specimens of the composition G series showed increasing corrosion damage as the nickel content increased. The samples containing between 0 and 3 percent nickel showed little evidence of attack. Severe corrosion damage first appeared on the alloy with 4 percent nickel. Corrosion damage was more severe on the samples with 6 percent and 9 percent nickel. These compositions apparently lack the ability to form a protective film at such high water velocity, as the macrostructure was clearly visible.

50. The three alloys of the composition M class also showed increasing corrosion attack as the nickel content was increased. The alloy of the regular composition showed no evidence of corrosion damage. Slight corrosion damage was visible on the leading edge of the alloy containing 1 percent nickel (M-1). The alloy with 3.5 percent nickel was without film protection, with the macrostructure clearly visible. Of the two 85-5-5-5 alloys, the one with 2.5 percent nickel was without film protection with the macrosturcture revealed. The alloy of standard composition was not visibly damaged.

Rotating cylindrical specimens:

51. The results of this test are shown graphically in Plate 12. The corrosion rate is expressed in milligrams per square inch per day. The specimens were removed after 28 days, washed off in tap water, dried and weighed.

52. Compositions G and M containing 0.75 percent and 1 percent nickel respectively, had slightly lower corrosion rates than the "nickel-free" compositions. The corrosion rates were increased by further substitution of nickel. The substitution of 2.5 percent nickel for 2.5 percent tin increased the corrosion rate of the 85-5-5-5 alloy.

53. The alloys with the lower corrosion rates were covered by a smooth, glazed film; those with higher rates were covered with a coarse, dull film. The least tenacious film formed on the specimens of the composition G group containing 6 percent nickel (G-2). Most of the film was removed from these specimens in cleaning. A dull red film completely covered the "tin-free", 9 percent nickel, composition G alloy.

Silicon bronze:

54. Although no data on cast silicon bronze are presented, the corrosion rate compared with the corrosion rate of the alloys in Plates 10, 11 and 12 has been reported previously (5). The composition of the silicon bronze tested is given in Table Ia, Item 2, Alloy No. 13. The corrosion rate in quiescent Severn River water which was 0.825, 0.830 and 1.05 milligrams per square inch per day for 40, 80 and 125 day tests, respectively, exceeded that of the standard and modified compositions. The corrosion rate when the specimen was moving 30 ft. per second was 5.1 and 10.0 milligrams per square inch per day for 28 and 69 day tests, respectively, and it exceeded the corrosion rate of the standard compositions in both the 28 and 69

day tests. However, the corrosion rate of the silicon bronze was exceeded in the 28 day test by "as cast" G-2, modified composition G in which the 9 percent tin was replaced by 9 percent nickel, modified composition M in which 3.5 percent tin was replaced by 3.5 percent nickel, and R.B.-1. The corrosion rate of the silicon bronze exceeded the corrosion rate of all compositions in the 69 day test excepting R,B.-1 with which it was identical. In general, the corrosion rate of the silicon bronze exceeds the corrosion rate of the standard and most of the modified compositions.

SUMMARY

(a) Composition G

55. The replacement of tin by nickel in composition G decreased intercrystalline shrinkage porosity. Physical properties which meet composition G specifications were obtained in all alloys except those containing 7.5 and 9 percent nickel.

56. The amount of tin which can be replaced by nickel depends on corrosion conditions. The corrosion rate of the motionless rectangular specimens in Severn River water was not affected by chemical composition, while the corrosion rate of the rectangular specimens, rotated at 30 ft. per second, increased as the tin content was decreased and replaced by nickel. A replacement of three percent tin by nickel seems to be maximum for this abnormally high velocity. The corrosion rate of the cylindrical specimens, rotated at 15 ft. per second, increased but little as the tin content was decreased and replaced by nickel . No marked composition limit was indicated in this test. (The corrosion rates of the specimens rotated at 30 ft. per second were not consistently higher than those for the specimens rotated at 15 ft. per second.

(b) Composition M and Red Brass

57. The replacement of tin by nickel in composition M and red brass did not effectively decrease intercrystalline shrinkage porosity, while all alloys met the physical property requirements for their respective basic compositions.

58. The corrosion rate of the motionless rectangular specimens in Severn River water was not affected

by variations in the chemical composition of composition M, but showed a definite, although slight, increase when 2.5 percent tin was replaced by 2.5 percent nickel in red brass (R.B.-1). The corrosion rate of the rectangular specimens, rotated at 30 ft. per second, definitely increased when 3.5 percent tin was replaced by 3.5 percent nickel in composition M, and when 2.5 percent tin was replaced by 2.5 percent nickel in red brass. A noticeable, but slight, increase in the corrosion rate of the cylindrical specimens was noted when the last two above mentioned alloys were revolved at 15 ft. per second. Although no corrosion data were obtained on composition M-2 it would seem that it would compare favorably with composition M in this regard in view of the present results.

CONCLUSIONS

59. (a) The replacement of tin by nickel decreases intercrystalline shrinkage porosity in composition G, but does not appreciably decrease porosity in composition M and red brass.

60. (b) The replacement of tin by nickel does not appreciably lower the physical properties of the basic compositions excepting the 7.5 and 9 percent nickel alloys in the G series.

61. (c) The extent to which tin is replaced by nickel in composition G and M and red brass for marine applications is determined by the corrosion conditions.

RECOMMENDATIONS

62. (a) As a conservation measure and as a means of improving casting quality, it is suggested that nickel replace tin in bronze of the compositions studied if the supply of tin becomes sufficiently acute to warrant such a replacement and if a supply of nickel or nickel scrap is available.

63. (b) Provided materials are available and since the replacement of tin by nickel improves internal soundness characteristics in composition G it is recommended that a closely supervised trial of composition G-2 be given at one of the Navy Yard foundries. Castings which are required to withstand hydrostatic pressure should be selected. A sufficient number of a particular casting should be made to determine the possibilities of the alloy. Care must be taken that the casting is not to be used in connection with high velocity water.

64. (c) Work should be continued with a view toward the elimination of gas porosity in composition G-2 and improving its resistance to corrosion in high velocity water with the introduction of certain elements that reduce corrosion.

FUTURE RESEARCH

65. A study of the molding and foundry technique of certain complicated castings is in progress with a view to producing sound pressure-tight castings.

66. A study of the width of the freezing range as a means of predicting casting qualities of new alloys is being made. For example, aluminum bronze has a very narrow solidification range (approximately 30°C) and it is usually internally sound, freezes with a deep pipe, has a very fine grain and unless pouring is accomplished with little or no turbulence cold shuts and rolled surface will result; while tin bronze has a very wide solidifaction range (approximately 200°C) and is characterized by its coarse grain, little or no external shrinkage or pipe, smooth surface, no cold shuts unless the pouring temperature is too low, and much internal unsoundness due to shrinkage.

67. A study of the elimination of gas porosity in tin bronze and its modifications by foundry tests is in progress.

68. A search for substitute alloys is still progressing.

ACKNOWLEDGMENT

69. The cooperation of the Naval Engineering Experiment Station, Annapolis, Maryland where the corrosion rate determinations were made is acknowledged.

REFERENCES

(1) The Causes for Porosity and Leakage in Non-Ferrous Castings, by A. H. Hesse, Naval Research Laboratory Report M-1650, dated 29 August 1940.

(2) The Fluidity of Cast Steel (Summary Report), by H. F. Taylor, E. A. Rominski and J. L. Darby, Naval Research Laboratory Report No.M-1657, 7 October 1940,

(3) General Specifications for Inspection of Material. Appendix II Metals, Part A-Definitions and Tests (Issued by the Navy Department, 1 June 1941).

(4) Manual on Presentation of Data, 1937, American Society for Testing Materials.

(5) Corrosion Tests of Non-Ferrous Casting as part of Naval Research Laboratory Investigation, EES Test B-4816, EES to Bureau of Ships, NP16/L5/JJ46 (1208-D), 3 February 1942.

ADDENDA

PART II

METHANE AND POROSITY

(a) Introduction

70. Such gases as hydrogen and water vapor were shown to cause much more porosity than sulphur dioxide carbon monoxide, nitrogen, oxygen and carbon dioxide(1) Sulphur dioxide seemed to have a minor deleterious effect, while the other gases except hydrogen and water vapor produced little, if any, precipitated gas porosity. Although no data were available, methane gas was thought to affect tin bronze in a manner similar to hydrogen and water vapor.

(b) Experimental Procedure

71. In view of the instructive results obtained from the original study(1) it was felt that the effect on porosity of the methane which is present should be investigated. Accordingly, a specimen of composition G was melted and solidified under commercial methane from which the oxygen and water vapor had been removed. The set-up for this determination is described in a preceding report(1) on pages 5 and 6, paragraphs 20, 21 and 22. The density of the resultant 3 pound specimen was determined, followed by sectioning lengthwise through the diameter for polishing and visual examination for voids.

(c) Discussion of Results

72. The density of the specimen melted and solidified under methane gas was 8.588 grams per cubic centimeter and the percent voids was calculated to be 3.8 by using 8.928 grams per cubic centimeter, as maximum density which was determined by the x-ray diffraction method. Thus methane causes more porosity than carbon dioxide and less porosity than sulphur dioxide (Plate 1, reference (1)). The longitudinal cross section polished through the diameter showed the flaky type of cavity illustrated for water vapor in Plate 8, reference (1). The cavities were not quite so large nor as abundant as those in the specimen melted under water vapor, which is indicated by a comparison of the percent voids in each (water vapor, 6.2 percent and methane, 3.8 percent). Methane can be responsible for some of the porosity in bronze castings, but to a minor extent only when compared with the effect of hydrogen and water vapor.

The explanation for the cause of the porosity depends upon the stability of methane gas in the presence of carbon and molten bronze, and the liquid and solid solubilities of methane or hydrogen or both in bronze, which may involve very complex reactions.

PART II

RESISTANCE TO CORROSION

(a) Preface

73. Since resistance to sea water corrosion is a very important requirement for bronzes which are used for marine applications, new substitute alloys which can replace the standard compositions even though they satisfy the mechanical requirements, must prove resistant to sea water corrosion. For this reason an extensive study of resistance to corrosion of standard copper alloys, modified compositions and potential substitute copper alloys was undertaken. Some work which has been completed by the Naval Engineering Experiment Station at Annapolis, Maryland, is incorporated in the main body of this report, while the work in progress at Annapolis, and at Wilmington,North Carolina, is outlined below as a matter of record.

(b) Annapolis, Maryland

74. Details of specimens submitted to the Naval Engineering Experiment Station are given in Tables Ia, IIa and IIIa. Results of tests on the material contained in Tables Ia and IIa have been reported previously(5) and are incorporated in the main body of this report. Results of tests on specimens in Table IIIa, have not been reported to this date, but work is in progress.

(c) Wilmington, North Carolina

75. The tests in slow moving sea water at the Dow Chemical Company, Wilmington, North Carolina are under the auspices of the International Nickel Company. Details are given in Tables IVa and Va. The tests on the specimens in Table IVa were begun in May 1941 and were removed, cleaned and weighed in May 1942. The corrosion rate of each specimen is given in Table VIa. Photographs which were taken of these specimens upon removal from the sea water and after they had been cleaned are on file at the Naval Research Laboratory. Since all specimens had approximately the same corrosion rate after one year's exposure and since the photographs did not show any striking difference, they are not being included in this report, nor are conclusions being presented.

TABLE I

X-RAY DENSITY VALUES FOR COMPOSITION "G" AND ITS MODIFICATIONS

SPECIMEN⁺ NUMBER	COMPOSITION, PER CENT					
	Copper	Tin	Nickel	Zinc*	Lead	X-ray Density, gms/cu.cm.
5	87.40	9.51		3.05	.04	8.933
28	87.75	8.20	1.12	2.93		8.926
65	88.30	7.12	1.99	2.59		8.930
41	88.42	5.93	2.97	2.68		8.914
46	88.36	4.94	4.17	2.51	.02	8.907
51	88.66	3.90	4.97	2.45	.02	8.927
36	88.75	2.94	5.98	2.33		8.928
56	88.29	1.58	7.41	2.70		8.922
61	88.93	0.00	8.97	2.10		8.928

* By difference

\+ Alternately cold compressed and annealed from 1" cubes to 1/4" x 1" x 1" pieces.

TABLE II

CHEMICAL ANALYSIS OF ALLOYS

ELEMENT		CHEMICAL COMPOSITION, PER CENT										
		G	G*	G-1	G-1*	G-2	G-2*	M	M-1	M-2	R.B.	R.B.-1
Copper	Nominal	88.0	88.0	88.0	88.0	88.0	88.0	88.0	88.0	86.0	85.0	85.0
	Maximum	88.9	88.9	88.8	88.4	89.0	88.8	88.2	89.9	86.5	85.4	85.9°
	Minimum	88.0	85.8	87.5	88.0	87.4	88.1	87.7	86.9	85.9	85.2	
Tin	Nominal	9.0	9.0	6.0	6.0	3.0	3.0	6.5	5.5	6.5	5.0	2.5
	Maximum	9.2	10.2	7.1	7.1	3.6	5.0	6.7	6.0	6.5	5.3	2.4°
	Minimum	7.8	7.7	4.3	5.9	2.4	2.9	6.3	4.7	6.1	4.8	
Nickel	Nominal	0.0	0.0	3.0	3.0	6.0	6.0		1.0	2.0		2.5
	Maximum	0.8	1.5	4.0	3.0	6.1	6.0		1.0	2.0		2.3°
	Minimum	0.0	0.0	2.0	2.0	5.6	4.2		1.0	2.0		
Zinc+	Nominal	3.0	3.0	3.0	3.0	3.0	3.0	4.0	4.0	4.0	5.0	5.0
	Maximum	3.0	3.3	4.0	2.8	3.9	2.8	4.2	4.4	4.3	4.7	4.8°
	Minimum	1.9	1.9	2.9	2.5	2.5	2.3	3.8	3.3	3.4	4.5	
Lead	Nominal	0.00	0.00	0.00	0.00	0.00	0.00	1.5	1.5	1.5	5.0	5.0
	Maximum	0.09	0.04	0.06	0.02	0.32	0.02	1.5	1.5	1.8	5.2	4.7°
	Minimum	0.00	0.00	0.00	0.00	0.00	0.00	1.3	1.1	1.1	4.9	
Number of Heats		7	8	7	4	6	6	5	7	4	3	1

R.B. - Red Brass

* Type 11A Test Mold; others type 10A Test Mold

\+ By difference

° Chemical analysis of one heat

TABLE III

DENSITY, TENSILE STRENGTH AND ELONGATION OF 7.5 AND 9 PER CENT NICKEL BRONZES

HEAT NUMBER	MOLD TYPE	COMPOSITION, PER CENT				POURING TEMPERATURE °C	POURING TEMPERATURE °F	DENSITY, gms. per cu. cm.	TENSILE STRENGTH, p.s.i.	ELONGATION, per cent
		Copper	Tin	Nickel	Zinc*					
35	11A	88.29	1.58	7.41	2.72	1320	2408	8.829	35,800	38.3
								8.809	37,000	39.1
						1230	2246	8.819	37,500	35.9
								8.837	37,800	35.9
						1180	2156	8.814	38,800	35.9
								8.800	31,100	12.5
						1140	2084	8.861	37,600	28.9
								8.802	37,700	32.8
						1090	1994	8.778	27,100	14.9
36	11A	88.93	0	8.97	2.10	1325	2417	8.868	28,700	28.1
								8.852	29,900	46.1
						1270	2318	8.813	32,300	31.3
								8.828	28,500	18.8
						1225	2237	8.827	27,200	20.3
								8.823	29,500	27.3
						1185	2165	8.873	30,900	30.5
								8.868	32,100	28.4
						1130	2066	8.755	19,800	11.7
								8.843	28,200	14.8
96	10A	89.17	0	8.88	1.95	1280	2336	8.976	29,900	28.1
								8.867	29,500	29.0
						1180	2156	8.851	31,900	42.2
								8.876	28,600	27.3
						1120	2048	8.872	33,100	33.6
								8.857	33,300	48.4
99	10A	88.48	0	9.17	2.35	1260	2300	8.855	28,500	22.7
								8.875	29,900	24.2
						1160	2120	8.865	29,000	26.6
						1090	1994	8.836	33,000	32.8
								8.824	33,000	35.2

* By difference

TABLE IV

COMPOSITION OF SEVERN RIVER WATER

pH 8.17

Residue on evaporation 11,866 ppm.

Positive Ions	ppm.	epm.	Negative Ions	ppm.	epm.
Iron, Fe ++	Trace	Trace	Silicate, SiO_3- -	7.6	0.2
Calcium, Ca ++	137	6.86	Carbonate, CO_3- -	0.01	-
Magnesium, Mg ++	397	33.10	Bicarbonate, HCO_3-	85.3	1.4
Sodium, Na ++	3250*	141.74	Chloride, Cl-	5770	162.7
			Sulfate, SO_4- -	833	17.4

ppm = parts per million

epm = equivalent parts per million

* By difference

TABLE Ia

CHEMICAL ANALYSIS OF BRONZE SPECIMENS FOR SEA WATER CORROSION TEST AT ANNAPOLIS, MARYLAND (1943)

ITEM 1

Alloy No.	Heat No.	Specimen No.		Chemical Composition * Desired ** Actual										
				Cu	Sn	Zn*	Ni	Pb	Al	Fe	Si	Mn		
1	80A	3-6-7-9-10	*	88.	9.	3.	—	—	—	—	—	—		G
		11-13 & 15	**	86.84	9.28	3.88	—	—	—	—	—	—		
2	83	1-2-3-4-5	*	88.	8.25	3.	0.75	—	—	—	—	—		
		11-12 & 13	**	87.52	8.63	3.12	0.73	—	—	—	—	—		
3	92	1-7-8-10-12	*	88.	7.	3.	2.	—	—	—	—	—		G-1
		13-14 & 15	**	88.06	7.11	2.87	1.96	—	—	—	—	—		
4	89	1-2-5-7-8	*	88.	6.	3.	3.	—	—	—	—	—		
		9-10 & 15	**	88.22	6.25	2.56	2.89	—	—	—	—	—		
5	90	1-2-3-4-6	*	88.	5.	3.	4.	—	—	—	—	—		
		10-11 & 12	**	88.78	4.25	2.95	4.02	—	—	—	—	—		
6	101	1-2-3-4	*	88.	3.	3.	6.	—	—	—	—	—		G-2
		& 6	**	88.62	2.89	2.61	5.88	—	—	—	—	—		
6	101B	1-2-3	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.53	3.04	2.34	5.76	.13	—	—	—	—		
6	107	5-9-11-14	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.65	3.05	2.75	5.49	.06	—	—	—	—	(a)	
6	107C	1-6-13-16	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.70	3.04	2.67	5.53	.06	—	—	—	—	(a)	
6	101	7-8-10-11	*	88.	3.	3.	6.	—	—	—	—	—		
		& 12	**	88.62	2.89	2.61	5.88	—	—	—	—	—	(b)	
6	101B	5-6-9	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.53	3.04	2.34	5.76	.13	—	—	—	—	(b)	
7	99	1-4-9-13	*	88.	—	3.	9.	—	—	—	—	—		
			**	88.60	—	2.47	8.79	.05	—	—	—	—		
7	99B	2-5-12-15	*	88.	—	3.	9.	—	—	—	—	—		
			**	88.66	—	2.46	8.84	.05	—	—	—	—		
8	97	1-2-3-5-8	*	88.	6.5	4.	—	1.5	—	—	—	—		M
		9-10 & 11	**	88.30	6.48	3.69	—	1.53	—	—	—	—		
9	91	1-2-4-7-9	*	88.	5.5	4.	1.	1.5	—	—	—	—		M-1
		11-12 & 13	**	88.16	5.80	3.58	0.96	1.50	—	—	—	—		
10	93	5-6-10-11	*	88.	3.	4.	3.5	1.5	—	—	—	—		
		12-13-14-15	**	87.88	3.24	3.74	3.44	1.70	—	—	—	—		
11	94	2-5-7-9-10	*	85.	5.	5.	—	5.	—	—	—	—		R.B.
		11-13 & 15	**	85.39	4.92	4.74	—	4.95	—	—	—	—		
12	98	1-2-5-6-7	*	85.	2.5	5.	2.5	5.	—	—	—	—		R.B.-1
		8-9 & 10	**	85.08	2.38	4.56	2.59	4.69	—	—	—	—		
13	95B	1-2-3-4-5	*	91.	1.	2.5	—	—	—	1.25	3.50	—		P.M.G.
		10-11 & 12	**	90.46	0.91	2.97	—	—	—	1.20	3.41	0.85		

* Zinc determined by difference

Note: Specimens are 2" wide by 1/2" thick by 6" long.
(a) "Aged"
(b) "Annealed"
others "As Cast"
Mechanical properties of all alloys except P.M.G. can be approximated by making use of curves, Plates 3, 4 and 5 contained in this report.

ITEM 2

Alloy No.	Heat No.	Specimen No.		Chemical Composition * Desired ** Actual										
				Cu	Sn	Zn*	Ni	Pb	Al	Fe	Si	Mn		
1	66	4	*	88.	9.	3.	—	—	—	—	—	—		G
			**	88.39	9.37	2.24	—	—	—	—	—	—		
2	65	3	*	88.	8.25	3.	0.75	—	—	—	—	—		
			**	88.12	8.18	2.97	0.73	—	—	—	—	—		
3	64	2	*	88.	7.	3.	2.	—	—	—	—	—		G-1
			**	88.27	7.01	2.81	1.81	—	—	—	—	—		
4	63	1	*	88.	6.	3.	3.	—	—	—	—	—		
			**	87.83	6.04	3.21	2.92	—	—	—	—	—		
5	61	4	*	88.	5.	3.	4.	—	—	—	—	—		
			**	88.34	5.02	2.62	4.03	—	—	—	—	—		
6	62	4	*	88.	3.	3.	6.	—	—	—	—	—		G-2
			**	88.68	2.96	2.41	5.95	—	—	—	—	—		
6	62	5	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.68	2.96	2.41	5.95	—	—	—	—	—	(a)	
6	62	6	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.68	2.96	2.41	5.95	—	—	—	—	—	(b)	
7	67A	1	*	88.	—	3.	9.	—	—	—	—	—		
			**	89.59	—	1.82	8.60	—	—	—	—	—		
8	68	2	*	88.	6.5	4.	—	1.5	—	—	—	—		M
			**	87.45	6.34	3.83	—	1.78	—	—	—	—		
9	70	4	*	88.	5.5	4.	1.	1.5	—	—	—	—		M-1
			**	88.39	5.52	3.75	0.49	1.85	—	—	—	—		
10	73	2	*	88.	3.	4.	3.5	1.5	—	—	—	—		
			**	89.11	2.81	3.06	3.44	1.38	—	—	—	—		
11	69	2	*	85.	5.	5.	—	5.	—	—	—	—		R.B.
			**	85.38	4.75	4.74	—	4.93	—	—	—	—		
12	71	3	*	85.	2.5	5.	2.5	5.	—	—	—	—		R.B.-1
			**	86.48	2.45	4.02	2.36	4.69	—	—	—	—		
13	72	1	*	91.	1.	2.5	—	—	—	1.25	3.50	0.75		P.M.G.
			**	90.48	0.84	2.97	—	—	—	1.08	3.82	0.61		

* Zinc determined by difference

Note: Specimens are 2" wide, 6" long and 1/2" thick.
Mechanical properties of all alloys except P.M.G. can be approximated by making use of curves, Plates 3, 4 and 5 contained in this report.
(a) "Aged"
(b) "Annealed"
[illegible]

TABLE IIA

CHEMICAL ANALYSIS OF BRONZE SPECIMENS FOR SEA WATER CORROSION TEST AT ANNAPOLIS, MARYLAND (1941)

ITEM 3

Alloy No.	Heat No.	Specimen No.		Total Length, Inches	Cu	Sn	Zn*	Ni	Pb	Al	Fe	Si	Mn		
					Chemical Composition * Desired ** Actual										
1	80	1	*	30	88.	9.	3.	—	—	—	—	—	—		[illegible]
			**		88.10	8.99	2.91	—	—	—	—	—	—		
1	80	2	*		88.	9.	3.	—	—	—	—	—	—		
			**		88.10	8.99	2.91	—	—	—	—	—	—		
1	80	4	*		88.	9.	3.	—	—	—	—	—	—		
			**		88.10	8.99	2.91	—	—	—	—	—	—		
2	83	1	*	25	88.	8.25	3.	0.75	—	—	—	—	—		
			**		87.52	8.63	3.12	0.73	—	—	—	—	—		
2	83	2	*		88.	8.25	3.	0.75	—	—	—	—	—		
			**		87.52	8.63	3.12	0.73	—	—	—	—	—		
2	83	4	*		88.	8.25	3.	0.75	—	—	—	—	—		
			**		87.52	8.63	3.12	0.73	—	—	—	—	—		
3	92	1	*	30	88.	7.	3.	2.	—	—	—	—	—		G-1
			**		88.06	7.11	2.87	1.96	—	—	—	—	—		
3	92	3	*		88.	7.	3.	2.	—	—	—	—	—		
			**		88.06	7.11	2.87	1.96	—	—	—	—	—		
3	92	5	*		88.	7.	3.	2.	—	—	—	—	—		
			**		88.06	7.11	2.87	1.96	—	—	—	—	—		
4	89	1	*	20	88.	6.	3.	3.	—	—	—	—	—		
			**		88.22	6.25	2.54	2.99	—	—	—	—	—		
4	89	3	*		88.	6.	3.	3.	—	—	—	—	—		
			**		88.22	6.25	2.54	2.99	—	—	—	—	—		
5	90	1	*	28	88.	5.	3.	4.	—	—	—	—	—		
			**		88.78	4.25	2.95	4.02	—	—	—	—	—		
5	90	2	*		88.	5.	3.	4.	—	—	—	—	—		
			**		88.78	4.25	2.95	4.02	—	—	—	—	—		
5	90	4	*		88.	5.	3.	4.	—	—	—	—	—		
			**		88.78	4.25	2.95	4.02	—	—	—	—	—		
6	101B	1	*	24	88.	3.	3.	6.	—	—	—	—	—		G-2
			**		88.53	3.04	2.34	5.76	.33	—	—	—	—		
6	101B	2	*		88.	3.	3.	6.	—	—	—	—	—		
			**		88.53	3.04	2.34	5.76	.33	—	—	—	—		
6	107C	1	*	20	88.	3.	3.	6.	—	—	—	—	—		
			**		88.70	3.04	2.67	5.53	.06	—	—	—	—	(a)	
6	107C	3	*		88.	3.	3.	6.	—	—	—	—	—		
			**		88.70	3.04	2.67	5.53	.06	—	—	—	—	(a)	
6	101	1	*	24	88.	3.	3.	6.	—	—	—	—	—		
			**		88.62	2.89	2.61	5.88	—	—	—	—	—	(b)	
6	101	2	*		88.	3.	3.	6.	—	—	—	—	—		
			**		88.62	2.89	2.61	5.88	—	—	—	—	—	(b)	
7	99	1	*	16	88.	—	3.	9.	—	—	—	—	—		
			**		88.69	—	2.47	8.79	.05	—	—	—	—		
7	99	2	*		88.	—	3.	9.	—	—	—	—	—		
			**		88.69	—	2.47	8.79	.05	—	—	—	—		
7	99B	1	*	8 1/2	88.	—	3.	9.	—	—	—	—	—		
			**		88.65	—	2.46	8.84	.05	—	—	—	—		
8	97	1	*	28	88.	6.5	4.	—	1.5	—	—	—	—		M
			**		88.30	6.48	3.69	—	1.53	—	—	—	—		
8	97	2	*		88.	6.5	4.	—	1.5	—	—	—	—		
			**		88.30	6.48	3.69	—	1.53	—	—	—	—		
8	97	4	*		88.	6.5	4.	—	1.5	—	—	—	—		
			**		88.30	6.48	3.69	—	1.53	—	—	—	—		
9	91	1	*	30	88.	5.5	4.	1.	1.5	—	—	—	—		M-1
			**		88.16	5.80	3.58	0.96	1.50	—	—	—	—		
9	91	2	*		88.	5.5	4.	1.	1.5	—	—	—	—		
			**		88.16	5.80	3.58	0.96	1.50	—	—	—	—		
9	91	3	*		88.	5.5	4.	1.	1.5	—	—	—	—		
			**		88.16	5.80	3.58	0.96	1.50	—	—	—	—		
10	93	1	*	30	88.	3.	4.	3.5	1.5	—	—	—	—		
			**		87.88	3.24	3.74	3.44	1.70	—	—	—	—		
10	93	2	*		88.	3.	4.	3.5	1.5	—	—	—	—		
			**		87.88	3.24	3.74	3.44	1.70	—	—	—	—		
10	93	3	*		88.	3.	4.	3.5	1.5	—	—	—	—		
			**		87.88	3.24	3.74	3.44	1.70	—	—	—	—		
11	94	1	*	29	85.	5.	5.	—	5.	—	—	—	—		N.2.
			**		85.39	4.92	4.74	—	4.95	—	—	—	—		
11	94	2	*		85.	5.	5.	—	5.	—	—	—	—		
			**		85.39	4.92	4.74	—	4.95	—	—	—	—		
11	94	3	*		85.	5.	5.	—	5.	—	—	—	—		
			**		85.39	4.92	4.74	—	4.95	—	—	—	—		
12	98	1	*	22	85.	2.5	5.	2.5	5.	—	—	—	—		N.B.-1
			**		85.88	2.28	4.56	2.59	4.69	—	—	—	—		
12	98	2	*		85.	2.5	5.	2.5	5.	—	—	—	—		
			**		85.88	2.28	4.56	2.59	4.69	—	—	—	—		
13	95B	1	*	22	91.	1.	2.5	—	—	—	1.25	3.50	—		P.M.G.
			**		90.46	0.91	2.97	—	—	—	1.20	3.61	0.85		
13	95B	2	*		91.	1.	2.5	—	—	—	1.25	3.50	—		
			**		90.46	0.91	2.97	—	—	—	1.20	3.61	0.85		

* Zinc determined by difference

Note: Specimens are 2 3/8" O.D. and 1" I.D.
Mechanical properties of all alloys except P.M.G. can be approximated by making use of curves, Plates 2, 4 and 5 contained in this report.
(a) "Aged"
(b) "Annealed"
others "As Cast"

CHEMICAL ANALYSIS AND PHYSICAL PROPERTIES OF SMALL SPECIMENS FOR SEA WATER CORROSION

TEST AT ANNAPOLIS, MARYLAND (1942)

Alloy No.	Heat No.	Specimen No.		Chemical Composition * Desired ** Actual									Tensile Strength P.S.I.	Percent Elongation 2"	
				Cu	Sn	Zn*	Ni	Pb	Al	Fe	Si	Mn			
1	155	1-3-4-5	*	88	6.5	4	—	1.5	—	—	—	—			
			**	88.4	6.6	3.4	—	1.6	—	—	—	—	37,800	23.4	
2	152	2-3-5-6	*	88	3.5	4	3	1.5	—	—	—	—			
			**	88.8	3.4	3.2	3.3	1.7	—	—	—	—	31,700	21.0	
3	156	1-2-3-4	*	87.5	3.5	4	3	1.5	—	0.5	—	—			
			**	87.8	3.5	3.9	3.0	1.4	—	0.4	—	—	30,600	26.6	
4	143	2-3-4-5	*	88	9	3	—	—	—	—	—	—			
			**	87.9	8.8	3.3	—	—	—	—	—	—	47,000	35.5	
5	180	1-2-3-6	*	88	3	3	6	—	—	—	—	—			
			**	88.6	3.0	2.3	6.1	—	—	—	—	—	40,600	32.3	
6	153	2-3-5-6	*	87.5	3	3	6	—	—	0.5	—	—			
			**	87.5	2.9	3.4	5.7	—	—	0.5	—	—	44,800	47.5	
7	148	1-3-4-6	*	85	6	3	6	—	—	—	—	—			
			**	84.9	6.0	3.1	5.9	—	—	—	—	—	50,500	43.0	
8	154	2-3-5-6	*	86.5	9	3	—	1.5	—	—	—	—			
			**	86.7	9.2	2.5	—	1.6	—	—	—	—	37,000	17.2	
9	147	1-3-4-5	*	86.5	5	3	4	1.5	—	—	—	—			
			**	86.9	4.8	2.5	4.0	1.7	—	—	—	—	39,000	20.0	
10	150	1-2-3-4	*	91	1	2.5	—	—	—	1.25	3.5	0.75			
			**	90.9	1.0	3.0	—	—	—	1.25	3.2	0.56	49,600	9.3	
11	12	1-2-3-4	*	88.2	—	—	—	—	8.6	2.9	—	—			
			**	88.0	—	—	—	—	8.9	2.9	—	—	60,000	22.0	N.D. 46-B-18c, QQ-B-671(A)
12	18	1-2-3-4	*	85.5	—	—	—	—	11	3.5	—	—			
			**	85.6	—	—	—	—	10.7	3.5	—	—	75,000	12	QQ-B-671(C)
13	157	1-2-3-4	*	85.5	—	—	—	—	11	3.5	—	—			
			**	85.1	—	—	—	—	10.6	3.5	—	—	75,000	12	QQ-B-671(C)
14	22	1-2-3-4	*	81.7	—	—	—	—	13.4	4.4	—	—			
			**	81.9	—	—	—	—	13.5	4.3	—	—	70,000	1.0	No government specification
15	A-3	1-2-3-4	*	89	—	—	—	—	10	1	—	—			
			**	89.5	—	—	—	—	9.5	0.9	—	—	70,000	30.0	QQ-B-671(B)sand cast, not heat-treated
16	40	1-2-3-4	*	90	—	—	—	—	10	—	—	—			
			**	89.9	—	—	—	—	9.5	0.5	—	—	65,000	25.0	No government specification
17	109B	1-2-3	*	63	—	—	10	—	—	—	—	27			
			**	66.0	—	—	10.0	—	—	—	—	22.6	84,700	37.6	
	109A	1	**	65.0	—	—	9.6	—	—	—	—	23.8			
18	163B	1-2-3	*	50	—	14	1	—	—	—	—	35			
			**	[illegible]	—	15.0	0.9	—	—	—	—	35.6	82,800	22.0	
	163A	1	*	48.3	—	15.5	1.0	—	—	—	—	35.2			
19	164B	1-2-3	*	46	—	14	5	—	—	—	—	35			
			**	47.0	—	15.7	4.7	—	—	—	—	30.4	83,200	36.0	
	164A	1	**	47.0		16.7	4.7	—	—	—	—	31.6			
20	165B	1-2-3	*	67	—	14	1	—	—	—	—	18			
			**	69.8	—	16.8	1.0	—	—	—	—	12.3	90,200	47.0	
	165A	1	**	66.1	—	16.1	1.2	—	—	—	—	16.6			

* Zinc determined by difference

N.B. All specimens were 8" x 1 1/2" x 3/8" with one side and one edge "machined" and the remaining sides and edges "as cast". Alloys numbered 11, 12, 13, 14, 15 and 16 are aluminum bronze of which number 13 was prepared by the Naval Research Laboratory and the remainder by Ampco Metal, Inc. No physical tests were made on these alloys and the figures shown are the minimum requirements of existing specifications. Alloys numbered 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 were tested at the Naval Research Laboratory and results given above are an average of two tests. Type 10A test casting in accordance with Navy Department Specification 46B8 was employed. Alloys numbered 17, 18, 19 and 20 were hot-forged and annealed for two hours at 1200° F. Physical tests were made on standard .313 inch tensile specimens.

TABLE IVa

CHEMICAL ANALYSIS OF BRONZE SPECIMENS FOR SEA WATER CORROSION
TEST AT WILMINGTON, NORTH CAROLINA (1941)

Alloy No.	Heat No.	Specimen No.	Chemical Analysis * Desired ** Actual	Cu	Sn	Zn‡	Ni	Pb	Fe	Al	Si	Mn		
1	66	1	*	88.	9.	3.	—	—	—	—	—	—		G
			**	88.39	9.37	2.24	—	—	—	—	—	—		
1	66	2	*	88.	9.	3.	—	—	—	—	—	—		
			**	88.39	9.37	2.24	—	—	—	—	—	—		
2	65	2A	*	88.	8.25	3.	0.75	—	—	—	—	—		
			**	88.12	8.18	2.97	0.73	—	—	—	—	—		
2	65	2B	*	88.	8.25	3.	0.75	—	—	—	—	—		
			**	88.12	8.18	2.97	0.73	—	—	—	—	—		
3	64	1	*	88.	7.	3.	2.	—	—	—	—	—		G-1
			**	88.27	7.01	2.81	1.91	—	—	—	—	—		
3	64	2	*	88.	7.	3.	2.	—	—	—	—	—		
			**	88.27	7.01	2.81	1.91	—	—	—	—	—		
4	63	1	*	88.	6.	3.	3.	—	—	—	—	—		
			**	87.83	6.04	3.21	2.92	—	—	—	—	—		
4	63	2	*	88.	6.	3.	3.	—	—	—	—	—		
			**	87.83	6.04	3.21	2.92	—	—	—	—	—		
5	61	2A	*	88.	5.	3.	4.	—	—	—	—	—		
			**	88.34	5.01	2.62	4.03	—	—	—	—	—		
5	61	2B	*	88.	5.	3.	4.	—	—	—	—	—		
			**	88.34	5.01	2.62	4.03	—	—	—	—	—		
6	62B	3A	*	88.	3.	3.	6.	—	—	—	—	—		G-2
			**	88.50	2.93	2.74	5.83	—	—	—	—	—		
6	62B	3B	*	88.	3.	3.	6.	—	—	—	—	—		
			**	88.50	2.93	2.74	5.83	—	—	—	—	—		
6	62E	2A	*	88.	3.	3.	6.	—	—	—	—	—		
			**	89.51	2.71	1.90	5.88	—	—	—	—	—	(a)	
6	62E	2B	*	88.	3.	3.	6.	—	—	—	—	—		
			**	89.51	2.71	1.90	5.88	—	—	—	—	—	(a)	
6	62E	3A	*	88.	3.	3.	6.	—	—	—	—	—		
			**	89.51	2.71	1.90	5.88	—	—	—	—	—	(b)	
6	62E	3B	*	88.	3.	3.	6.	—	—	—	—	—		
			**	89.51	2.71	1.90	5.88	—	—	—	—	—	(b)	
7	67A	1	*	88.	—	3.	9.	—	—	—	—	—		
			**	89.59	—	1.81	8.60	—	—	—	—	—		
7	67A	2	*	88.	—	3.	9.	—	—	—	—	—		
			**	89.59	—	1.81	8.60	—	—	—	—	—		
8	68	5	*	88.	6.5	4.	—	1.5	—	—	—	—		M
			**	87.45	6.94	3.83	—	1.78	—	—	—	—		
8	68	6	*	88.	6.5	4.	—	1.5	—	—	—	—		
			**	87.45	6.94	3.83	—	1.78	—	—	—	—		
9	70	1	*	88.	5.5	4.	1.	1.5	—	—	—	—		M-1
			**	88.19	5.52	3.75	0.99	1.55	—	—	—	—		
9	70	2	*	88.	5.5	4.	1.	1.5	—	—	—	—		
			**	88.19	5.52	3.75	0.99	1.55	—	—	—	—		
10	73	1	*	88.	3.	4.	3.5	1.5	—	—	—	—		
			*	89.31	2.81	3.06	3.44	1.38	—	—	—	—		
10	73	2	*	88.	3.	4.	3.5	1.5	—	—	—	—		
			**	89.31	2.81	3.06	3.44	1.38	—	—	—	—		
11	69	1	*	85.	5.	5.	—	5.	—	—	—	—		R.B.
			**	85.38	4.95	4.74	—	4.93	—	—	—	—		
11	69	2	*	85.	5.	5.	—	5.	—	—	—	—		
			**	85.38	4.95	4.74	—	4.93	—	—	—	—		
12	71	1	*	85.	2.5	5.	2.5	5.	—	—	—	—		R.B.-1
			**	86.48	2.45	4.02	2.36	4.69	—	—	—	—		
12	71	2	*	85.	2.5	5.	2.5	5.	—	—	—	—		
			**	86.48	2.45	4.02	2.36	4.69	—	—	—	—		
13	72	1	*	91.	1.	2.5	—	—	1.25	—	3.5	0.75		P.M.G.
			**	90.48	0.84	2.97	—	—	1.08	—	3.82	0.81		
13	72	2	*	91.	1.	2.5	—	—	1.25	—	3.5	0.75		
			**	90.48	0.84	2.97	—	—	1.08	—	3.82	0.81		

‡ Zinc determined by difference

Note: Specimens are 5" wide, 12" long and 3/8" thick.
Mechanical properties of all alloys except P.M.G. can be approximated by making use of curves, Plates 2, 4 and 5 contained in this report.
(a) "Aged"
(b) "Annealed"
others "As Cast"

TABLE Va

CHEMICAL ANALYSIS AND PHYSICAL PROPERTIES OF BRONZE SPECIMENS FOR SEA WATER CORROSION

TEST AT WILMINGTON, NORTH CAROLINA -(1942)

Alloy No.	Heat No.	Specimen No.		Chemical Composition * Desired	** Actual								Tensile Strength P.S.I.	Percent Elongation 2"	
				Cu	Sn	Zn*	Ni	Pb	Al	Fe	Si	Mn			
1	155	5-6	*	88	6.50	4	—	1.5	—	—	—	—			
			**	88.4	6.57	3.39	—	1.64	—	—	—	—	37,800	23.4	
2	151	4-6	*	88	3.50	4	3	1.5	—	—	—	—			
			**	88.8	3.77	3.81	3.26	0.68	—	—	—	—	31,700	21.0	
3	156	3-4	*	87.5	3.50	4	3	1.50	—	0.50	—	—			
			**	87.7	3.52	3.89	3.03	1.39	—	0.42	—	—	38,600	26.6	
4	143	1-4	*	88	9	3	—	—	—	—	—	—			
			**	87.9	8.80	3.25	—	.02	—	—	—	—	47,000	35.5	
5	158	3-6	*	88	3	3	6	—	—	—	—	—			
			**	87.8	2.93	2.93	6.19	.08	—	—	—	—	40,600	32.3	
6	153	5-6	*	87.5	3	3	6	—	—	0.50	—	—			
			**	87.5	2.91	3.37	5.68	—	—	0.53	—	—	44,800	47.5	
7	148	3-4	*	85	6	3	6	—	—	—	—	—			
			**	84.9	6.00	3.14	5.94	—	—	—	—	—	50,500	43.0	
8	154	1-3	*	86.5	9	3	—	1.50	—	—	—	—			
			**	86.7	9.16	2.48	—	1.61	—	—	—	—	37,000	17.2	
9	147	1-4	*	86.5	5	3	4	1.50	—	—	—	—			
			**	86.9	4.85	2.54	4.01	1.68	—	—	—	—	39,000	20.0	
10	150	1-6	*	91	1	2.50	—	—	—	1.25	3.50	0.75			
			**	90.9	1.04	3.06	—	—	—	1.25	3.20	0.56	49,600	9.3	
11	12	1-2	*	88.5	—	—	—	—	8.60	2.90	—	—			
			**	88.0	—	—	—	—	8.89	2.91	—	—	60,000	22.0	N.D. 46-B-18c, QQ-B-671 "A"
12	18	1-2	*	85.5	—	—	—	—	11.00	3.50	—	—			
			**	85.5	—	—	—	—	10.68	3.50	—	—	75,000	12	QQ-B-671 (C)
13	157	3-6	*	85.5	—	—	—	—	11.00	3.50	—	—			
			**	85.1	—	—	—	—	10.59	3.45	—	—	75,000	12	QQ-B-671 (C)
14	22	1-2	*	81.7	—	—	—	—	13.40	4.40	—	—			
			**	81.9	—	—	—	—	13.50	4.38	—	—	70,000	1.0	No government specification
15	A-3	1-2	*	89	—	—	—	—	10	1	—	—			
			**	89.5	—	—	—	—	9.49	0.98	—	—	70,000	30.0	QQ-B-671a, class B, sand cast, unheat-treated.
16	40	1-2	*	90	—	—	—	—	10	—	—	—			
			**	89.9	—	—	—	—	9.47	0.46	—	—	65,000	25.0	No government specification

* Zinc determined by difference

N.B. All specimens were 12" x 1 1/2" x 1/4" with one side and one edge"machined" and the remaining sides and edges "as cast". Alloys numbered 11, 12, 13, 14, 15 and 16 are aluminum bronze of which number 13 was prepared by the Naval Research Laboratory and the remainder by Ampco Metal, Inc. No physical tests were made on these alloys and the figures shown are the minimum requirements of existing specifications. Alloys numbered 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 were tested at the Naval Research Laboratory and results given above are an average of two tests. Type 10A test casting in accordance with Navy Department Specification 46B8 was employed.

TABLE VIa

CORROSION RATE IN SEA WATER AT WILMINGTON, NORTH CAROLINA

FIRST YEAR (1941-1942)

Alloy No.	Heat No.	Specimen No.	Original Wt. ~~GMS.~~ Gms.	Wt. as of May, 1942 ~~GMS.~~ Gms.	Wt. Loss After 347 Days Exposure ~~GMS.~~ Gms.	Corrosion Rate Mg/Sq.In/Day
1	66	1	3055	3049	6	0.13
1	66	2	3146	3142	4	0.09
2	65	2-A	3120	3117	3	0.07
2	65	2-B	3107	3102	5	0.11
3	64	1	3034	3029	5	0.11
3	64	2	3039	3034	5	0.11
4	63	1	3080	3077	3	0.07
4	63	2	2993	2995	+2	+0.04
5	61	2-A	2965	2962	3	0.07
5	61	2-B	3023	3019	4	0.09
6	62-B	3-A	3070	3064	6	0.13
6	62-B	3-B	2964	2954	10	0.22
6	62-E	2-A	2958	2950	8	0.18
6	62-E	2-B	3005	3000	5	0.11
6	62-E	3-A	3077	3072	5	0.11
6	62-E	3-B	3177	3168	9	0.2
7	67-A	1	3148	3142	6	0.13
7	67-A	2	3147	3147	0	0.00
8	68	5	3013	3012	1	0.02
8	68	6	3042	3037	5	0.11
9	70	1	3167	3160	7	0.15
9	70	2	2975	2967	8	0.18
10	73	1	2910	2905	5	0.11
10	73	2	2982	2979	3	0.07
11	69	1	3013	2982	31	0.68
11	69	2	3142	3134	8	0.18
12	71	1	3215	3211	4	0.09
12	71	2	3302	3297	5	0.11
13	72	1	2760	2759	1	0.02
13	72	2	2815	2813	2	0.04

See Table IV~~A~~a for details.

X-RAY DIFFRACTION DENSITY DETERMINATIONS

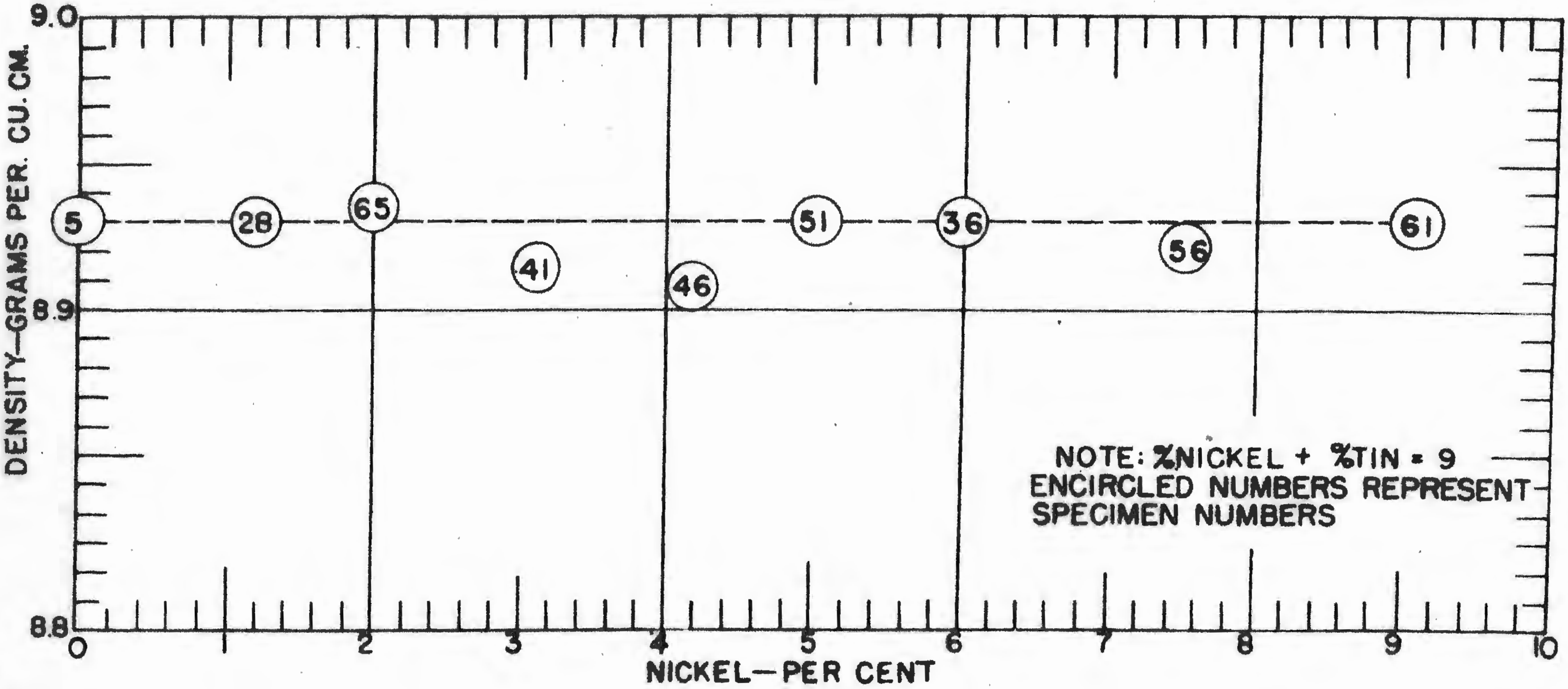
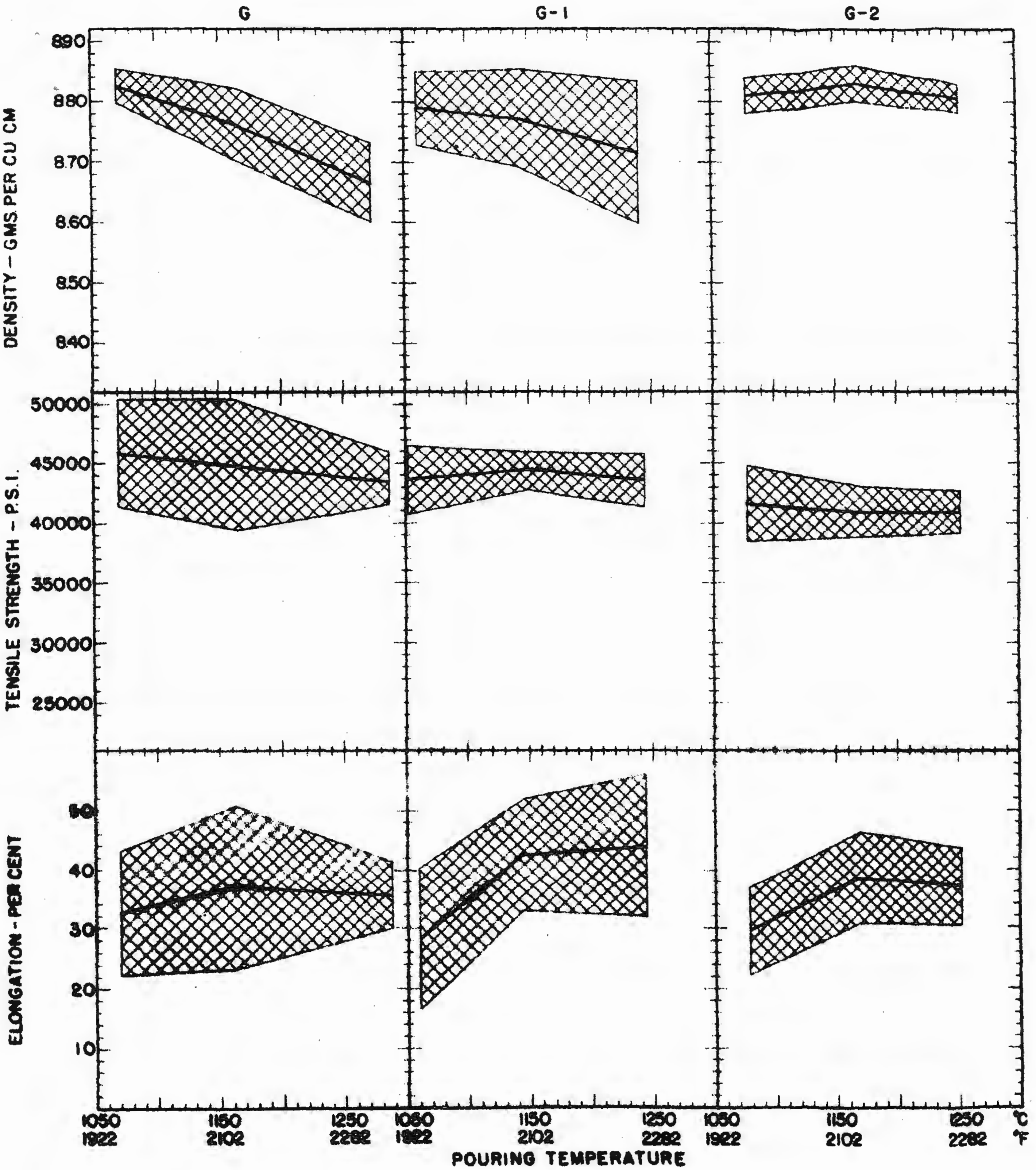
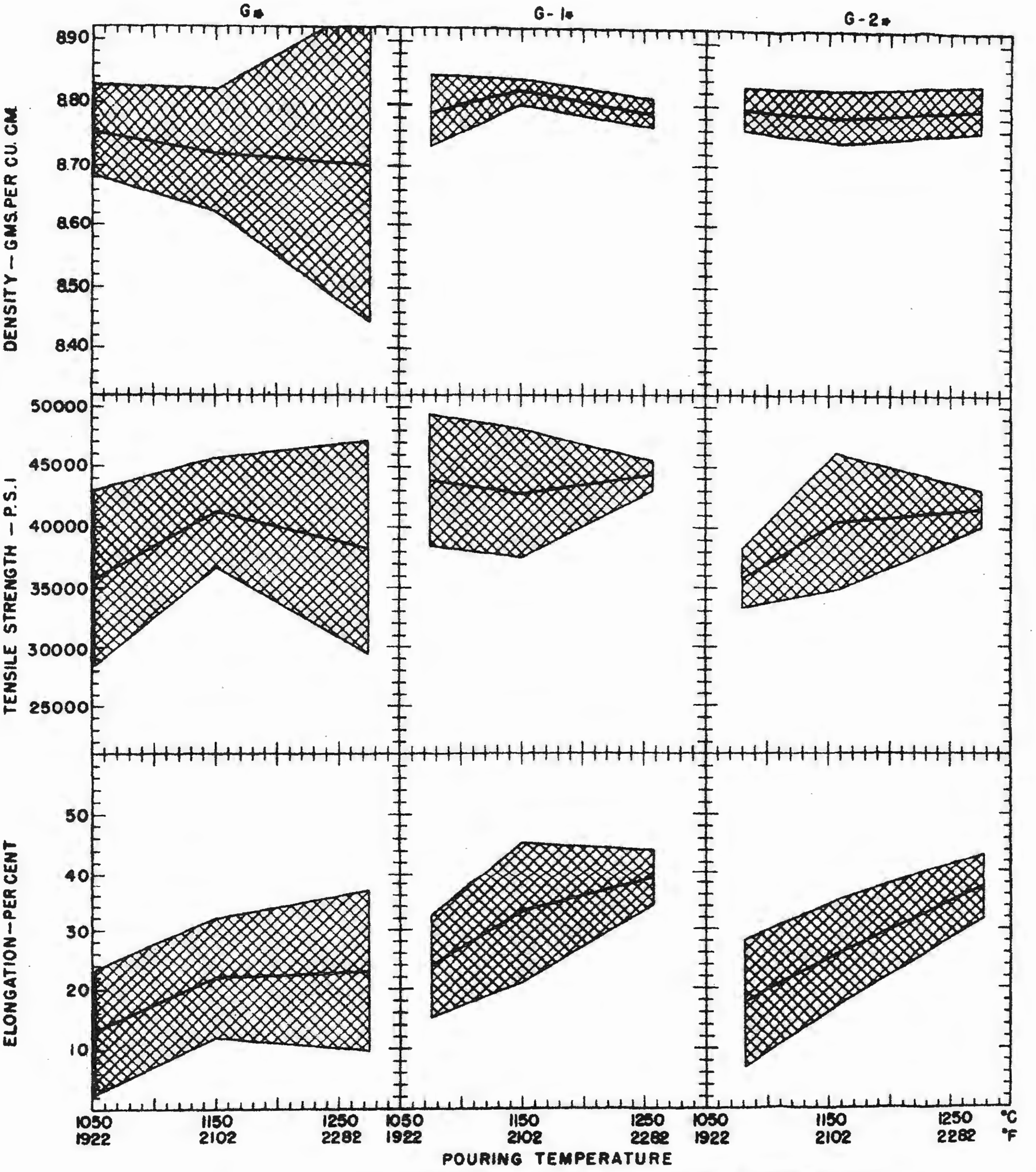


PLATE I

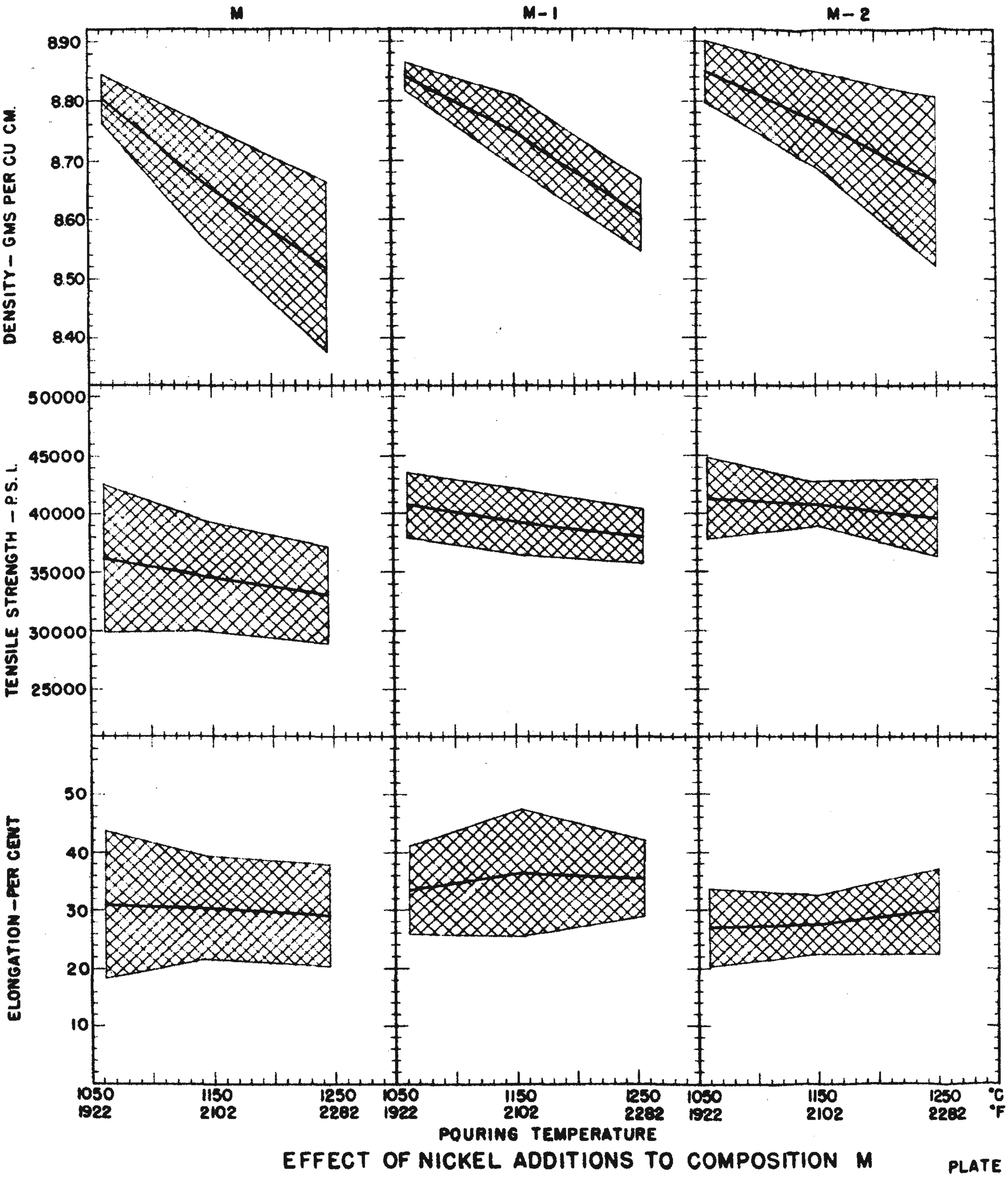


EFFECT OF SUBSTITUTING NICKEL FOR TIN IN COMPOSITION G

PLATE 2

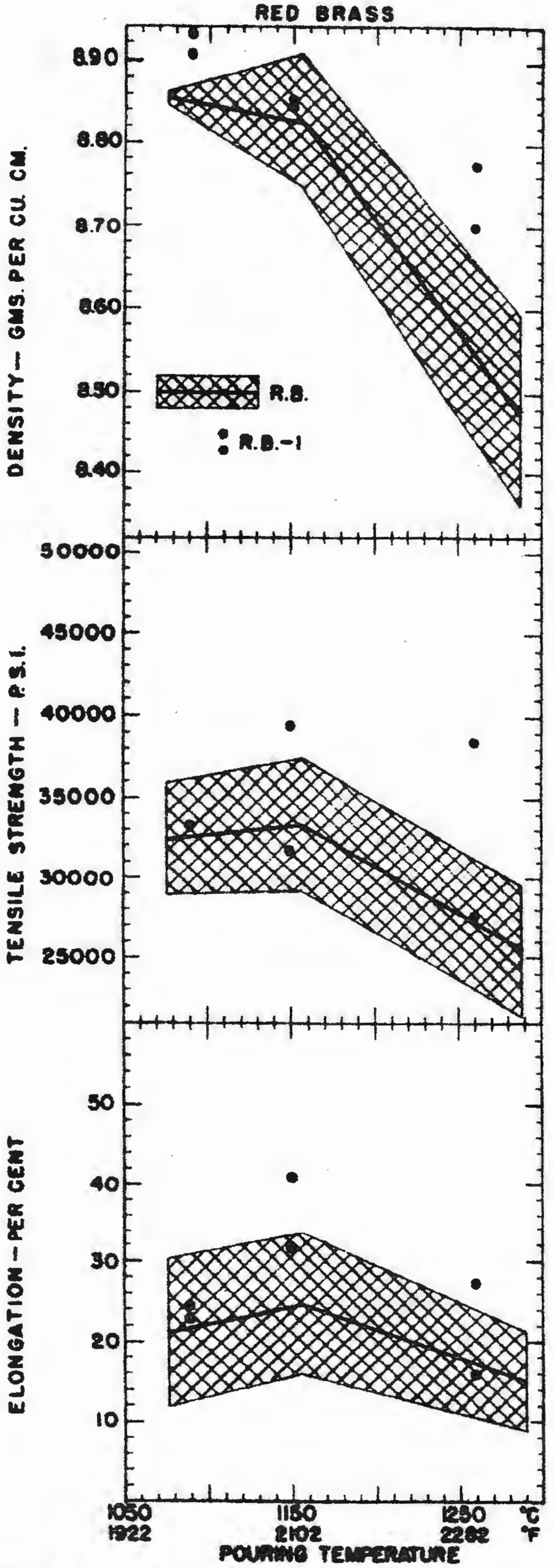


EFFECT OF SUBSTITUTING NICKEL FOR TIN IN COMPOSITION G PLATE 3

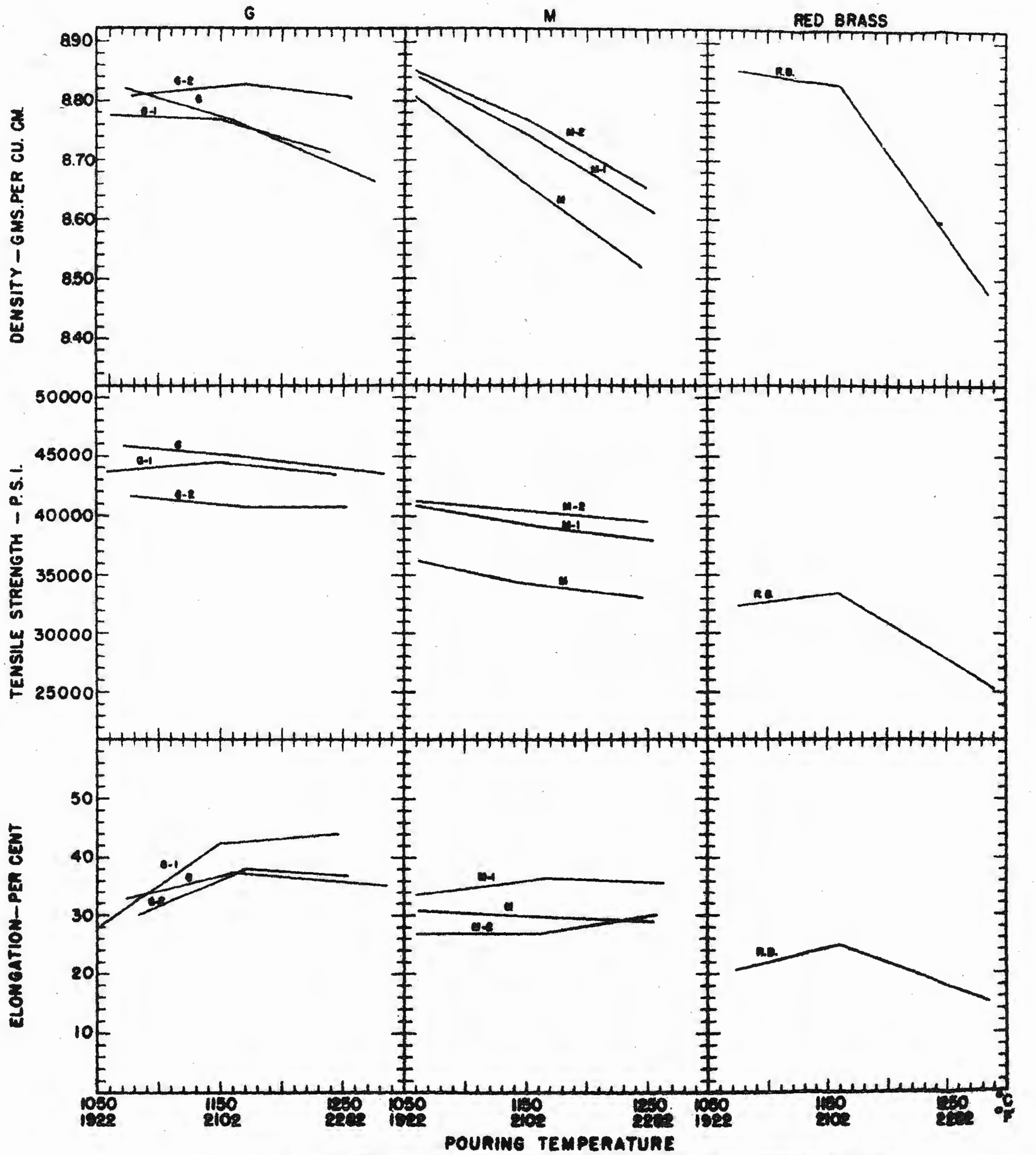


EFFECT OF NICKEL ADDITIONS TO COMPOSITION M

PLATE 4



EFFECT OF SUBSTITUTING NICKEL FOR TIN IN RED BRASS (10A TEST MOLD) PLATE 5



MEAN CURVES FOR TIN BRONZES AND THEIR MODIFICATIONS

PLATE 6

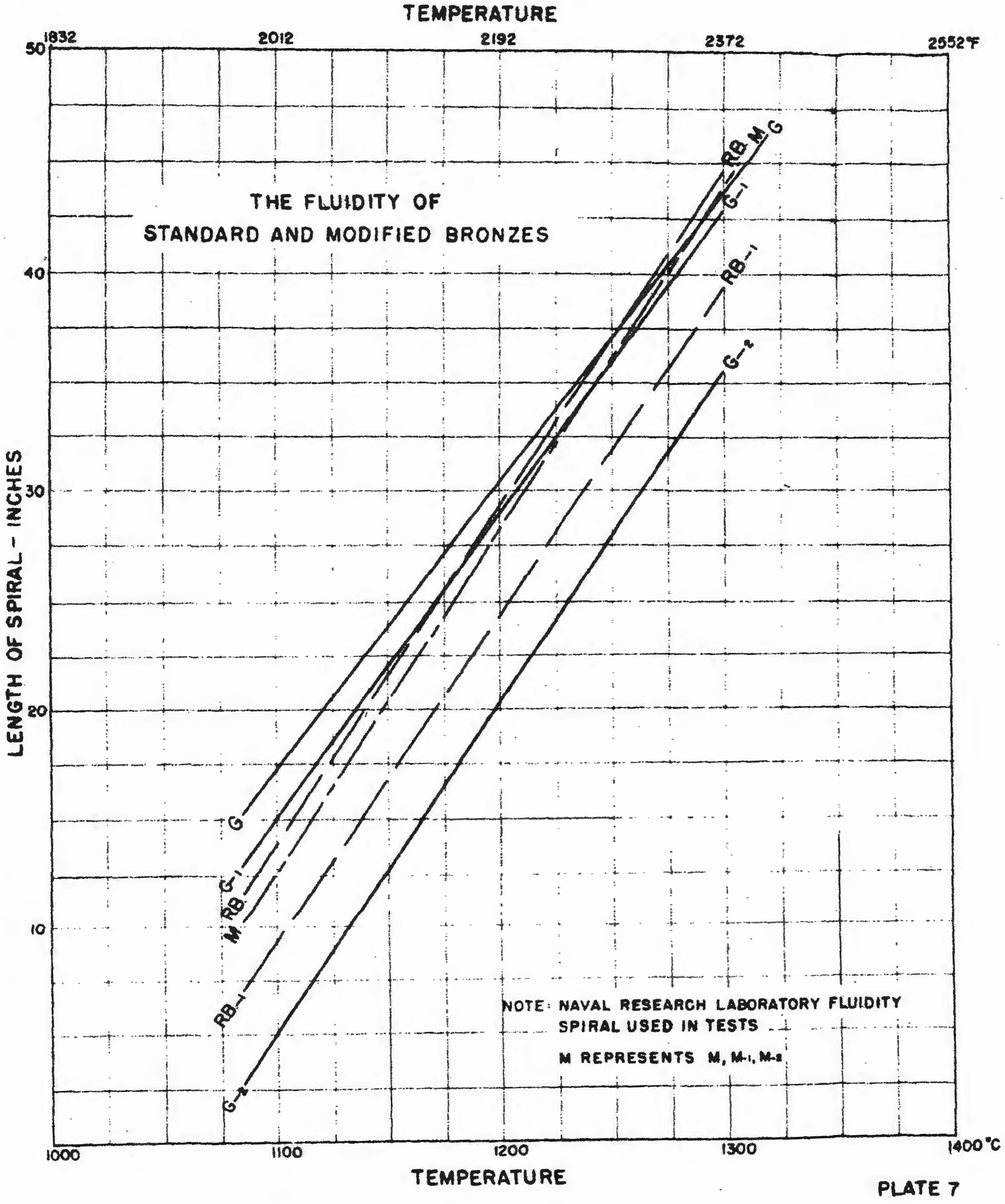

TEMPERATURE
1832
2012
2192
2372
2552°F
THE FLUIDITY OF
STANDARD AND MODIFIED BRONZES
LENGTH OF SPIRAL - INCHES
50
40
30
20
10
RB M G
G-1
RB-1
G-2
G
G-1
RB
M
RB-1
G-2
NOTE: NAVAL RESEARCH LABORATORY FLUIDITY
SPIRAL USED IN TESTS
M REPRESENTS M, M-1, M-2
1000
1100
1200
1300
1400°C
TEMPERATURE

PLATE 7