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on

Low Expansion Alloys for Main Steam Lines

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ABSTRACT

The properties of some low expansion alloys were studied with the purpose of determining their suitability for main steam lines aboard ship. Alloys of iron-nickel and iron-nickel-cobalt were prepared and their thermal expansion, physical properties and corrosion resistance were studied. In some alloys a material reduction in expansion could be obtained by heat treatment. However, heating to high temperatures destroyed the low expansion properties. An alloy containing Fe-54%, Ni-28%, and Co-18% has an excellent combination of low expansion, low modulus and high elastic limit. This alloy had an average expansion one-fourth that of carbon molybdenum steel between 70° and 800° F.

FEB 8 - 1940

Table of Contents

Appendices

INTRODUCTION

(a) Authorization

1. The studies in low expansion alloys were originally authorized by Bureau of Engineering letter L1-2/NP14(12-1-Fs) of 1 December 1938, Bureau of Engineering Project 144/39.

(b) Statement of Problem

2. The purpose of this investigation is to study the properties of low expansion alloys at high temperatures, with the object of determining their suitability for main steam lines in warships.

(c) Known Facts Bearing on the Problem (Theoretical Consideration)

3. This study is of practical importance in the designing of high temperature equipment, particularly in high pressure, high temperature steam lines. In the design of high temperature steam lines, the expansion must be counteracted by use of expansion joints which are a source of trouble and require frequent overhaul. The steels in present use, either Bain metal or carbon-molybdenum steels, are subject to decarbonization and hydrogen embrittlement and have rather low physical properties at elevated temperatures.

4. It is known that Invar type alloys have good high temperature strength, shock resistance, and corrosion resistance. Furthermore, they may be forged, welded and machined much as any steel. There is, therefore, every reason to expect that such an alloy may prove to be suitable for main steam lines and thus eliminate much of the expansion trouble at the source. The proposal was, therefore, made by this Laboratory that the well-known series of low expansion alloys be investigated in order to determine their suitability for this application.

5. These alloys, although starting with a very low coefficient at room temperature, may expand more than ordinary steels at some higher temperature. This is illustrated in Plate 1. The coefficients of expansion of ordinary carbon steel are plotted against the temperature. Accompanying this curve is a similar curve for a 36 per cent nickel-iron (Invar). Plate 1 shows that Invar expands more rapidly than the ordinary carbon steel after the temperature has attained 525° F. The total expansion from room temperature to any given temperature is, however, less for the Invar than the carbon steel (Plate 2). The sharp break in the curve at approximately 500° F will be referred to as the inflection point.

6. Although the literature contains many references to low expansion alloys, the work is mainly confined to the expansivity in the vicinity of room temperature or to special purpose alloys such as glass seal-ins. The published work on low expansion at higher temperatures is extremely limited. A list of important papers on the subject will be found in Appendix 1.

7. The factors which influence the expansivity of low expansion alloys are composition, heat treatment and mechanical treatment. Guillaume[4] investigated the effect of C, Mn, Cu, and Cr on the expansion of iron-nickel alloys. His results show that when Mn and Cr are present, the nickel content must be increased to obtain the minimum expansion while carbon and copper decrease it. Scott[5] studied the effect of Mn and Si on inflection points and expansion coefficient of a 45 per cent Ni alloy. The addition of 1 per cent Mn was found to lower the inflection point and raise the minimum coefficient of expansion. Silicon below 1 per cent had no appreciable effect, but above 1 per cent it lowered the inflection point but did not affect the minimum coefficient. Hunter[6] claims that tungsten and molybdenum have an effect similar to manganese and chromium in that the nickel content required for minimum coefficient of expansion is increased.

8. Scott[7] in his work on Fe-Ni-Co alloys found that when Co was substituted for Ni, the low expansivity was extended over a large range of temperatures. While the substitution of Co for Ni did not change the inflection temperature, the average coefficient of expansion was materially lowered. The maximum amount of Co which could be substituted for nickel was limited by the necessity of keeping the Ar_3 transformation well below room temperature.

9. Guillaume[8] found that the coefficient of expansion of the Invar type alloys can be changed by mechanical and thermal treatment. Annealing tends to increase the coefficient and rapid cooling tends to decrease the value. The coefficient can be more effectively lowered by cold working, and it is possible to produce at times even negative values.

10. The general basis of the low-expansion phenomenon can be stated as follows: When pure iron (alpha iron) is heated to 760° C (1400° F), it becomes non-magnetic, although its crystal structure does not alter. When it is heated still higher to 910° C (1670° F), it changes its crystal structure and becomes gamma iron. The non-magnetic alpha iron existing between 760° C and 910° C is sometimes called beta iron, but this term has been generally abandoned, since it has been proved that no new crystal phase comes into being when the magnetic change takes place.

11. When iron is alloyed with nickel, the latter very much lowers the temperature of the gamma transformation until at 30 per cent nickel the gamma phase is stable at room temperature and the alloy must be brought to a sub-zero temperature to obtain the alpha phase. Nickel also lowers the magnetic transformation point, but not as low as the gamma-alpha transformation. A 36 per cent nickel-rion at room temperature has the paradoxical property of having the gamma iron structure, but being still magnetic.

12. The peculiar property of all these alloys containing over 30 per cent nickel is that they have a very low expansion in the short range of temperature between the gamma-alpha and the magnetic transformation, and that they go through this range reversibly; i.e., without temperature hysteresis.

13. As stated before, the low expansion properties are associated with a lowering of the gamma to alpha transformation below room temperature and a corresponding lowering of the alpha to gamma transformation. The transformation temperatures on heating and cooling are not the same, but may differ by as much as 600° C, depending upon the composition. This range of temperature difference between the alpha to gamma and the gamma to alpha transformation is important when the stability of the alloys is concerned. Since the low expansion anomaly is a property of the gamma phase and not of the composition, it is seen that if the temperature is lowered sufficiently to permit the formation of some alpha phase, the low expansion properties will be impaired in proportion to the percentage formed. Also, in general, in order to preserve the stability, any condition that may bring about a transformation to the alpha phase must be avoided. In some respects the Invars resemble other types of austenitic steels in stability. Wymen and Scheil[3] have shown that an Invar of the Fe-Ni-Co type will undergo a gamma to alpha transformation on cold working. This decomposition is very similar to that of the stainless 18-8 Cr-Ni steels which suffers a similar breakdown on cold working. This instability has the effect of limiting the compositions possible for low expansion alloys in that the gamma to alpha transformation must be sufficiently suppressed below room temperature to assure stability. In a similar manner, heating to high temperature has the effect of increasing the expansivity. Hessenbruck[2] has found that in the commercial application of Kovar, used for sealing into glass, the expansion characteristics of the alloy were changed by heating to the sealing temperature. This heating has the effect of raising the temperature of the gamma to alpha transformation. If this transformation is raised above room temperature, the alloy will, on cooling, form some alpha phase, and in so doing will cause the alloy to become irreversible. The reason for the raising of the gamma to alpha transformation is not well understood; however, it is an experimental fact that it is associated with grain growth. Consequently, any treatment that will increase grain size should be avoided.

(d) Narrative of Original Work done at this Laboratory.

14. The study of determining the suitability of low expansion alloys to high temperature steam lines consisted of preparing alloys of Fe-Ni and Fe-Ni-Co and measuring the expansion characteristics, corrosion and physical properties at elevated temperatures. The measurements of the expansion properties were made in a dilatometer constructed at this Laboratory. The tensile strength, elastic limit and modulus were measured at elevated temperatures; namely, 70, 300, 600, 800, and 900° F. The measurement of these physical properties presented some difficulty because of the high temperatures involved. For this purpose a new type extensometer was designed and built at this Laboratory.

METHODS

(a) Preparation of Materials

15. Table 1 gives the actual composition of the alloys produced. These alloys were prepared from Armco iron, electrolytic nickel and

FEB 8 - 1940

commercial cobalt. (Analysis given in Table 1.) The melting was carried out in an Ajax high frequency induction furnace in magnesia crucibles. The 15-pound heats obtained were poured into iron ingot molds and forged at 1900° F - 2200° F into one and two-inch round stock. The melts were deoxidized by suitable additions of ferrotitanium or ferrosilicon.

(b) Description of Experiments

Expansion Apparatus

16. A dilatometer (Plates 3 and 4) was constructed to measure the expansion properties. The apparatus consisted of a furnace (A) into which is placed a heavy iron cylindrical block (B) to minimize temperature gradients which might otherwise be present. The specimen (S) is placed in the cylindrical hole and a quartz rod (C) is supported on its top. A quartz tube (D) is placed over the two-inch specimen and rests on the flanged base. At the top of the quartz tube, a dial holder was attached by means of a multi-split brass tube and held securely by means of a ring containing screws which tighten on the split brass tube. An Ames dial, graduated to 1/10,000 of an inch, was used to measure the expansion. A Chromel-Alumel thermocouple was inserted in a hole drilled in the base of the specimen. The leads were taken through the bottom of the block by grooves cut for this purpose to a portable Leeds and Northrup potentiometer.

Corrosion Apparatus

17. An apparatus was constructed to study the effect of steam and atmospheric corrosion at 1,000° F. The apparatus for the steam corrosion test consisted of a perforated shell into which a two-inch perforated nickel tube was inserted. The specimens under test were strung through their centers on a stainless steel rod and placed inside the two-inch tube. The apparatus was placed in a muffle furnace and steam produced by allowing water to drop into the hot furnace. The atmospheric test was also conducted in the same furnace. In this case a two-inch nickel tube was placed in the furnace and the mouth of the tube exposed to the air. The corrosion specimens consisted of 5/8-inch diameter by 1/32-inch discs.

Description of Extensometer

18. The whole assemblage of furnace specimen and extensometer is shown from front and rear in Plates 5 and 6.

19. The specimens were mounted in a split type combustion furnace. Molybdenum wires, two inches apart, were attached to the specimen by two hardened knife-edged steel rings, which were held in place by the tension produced by weights attached to the ends of the wires. The wires were led from the furnace through slits provided for that purpose. All other openings were tightly packed with asbestos fiber to diminish temperature gradients. The temperature of the specimen was measured with a chromel-alumel thermocouple wrapped around the central portion of the test specimen. The thermocouple wires were insulated with refractory beads and led through the top of the furnace.

20. Exactly half-way between the attachments of the wires to the specimen and the centers of the pulleys the extensometer was mounted, which, therefore, measured half the total elongation of the specimen. This instrument consists of a pair of 32 mm microscope objectives which are focussed on the wires. Behind these objectives is a system of aluminized mirrors arranged to bring the images of both wires to a common focus in a microscope eyepiece. When the wires are exactly two inches apart, the two images fuse into one, but as the specimen elongates the images separate. The lower of the two objectives is carried by a moveable slide running on steel balls between steel guides and raised or lowered by means of a micrometer screw. The latter is coupled by means of gearing to a revolution counter easily visible to the operator. This revolution counter reads elongations directly to .0001 inch per inch.

21. The tensile specimens used were 0.313 inch diameter, two-inch gauge length, with threaded ends, and were machined from forged stock.

DATA OBTAINED

Expansion Characteristics

22. The expansion curves obtained are given on Plates 7 to 22 inclusive, and a summary of the mean coefficients of expansion is given in Table 2. A plot of the expansion of alloy 2 is given in Plate 7. The expansion characteristics of this 61 per cent Fe, 39 per cent Ni alloy are typical of low expansion alloys in that there is a region of low expansivity up to the inflection point at 200° C where the curve begins to increase its slope and the alloy expands rapidly.

23. To ascertain the effect of molybdenum, alloy 3 (1.70 per cent Mo), Plate 8, and alloy 4 (3.9 per cent Mo) were prepared. Plate 9 shows that such an addition increases the expansivity when compared with the base composition of alloy 2. Plates 10 to 14 show the effect of heat treatment on alloy 5, which contains 28 per cent Ni and 18 per cent Co. In the as forged condition, (Plate 10), the expansivity is high and is approximately linear throughout the temperature range and there is no inflection point. When the expansion specimen was heated to 600° C (1112° F) for 24 hours and furnace-cooled, the expansivity, Plate 11, was lowered and an inflection point occurred at approximately 425° C. Holding this alloy at 700° C (1290° F) for 24 hours also produced a marked decrease in the expansivity, Plate 12. The effect of this anneal was quite beneficial and the average coefficient of expansion at 450° C (842° F) decreased from 6.8×10^{-6} per degree C in the as forged condition to 4.4×10^{-6} per degree C in the annealed condition.

24. To determine the effects of a prolonged annealing on the expansion of alloy 5, the e x pansion specimen was sealed in a glass tube and held for 348 hours at 540° C (1,000° F). The expansivity, Plate 13, was lower than after the 700° C anneal. The curve begins with a small

negative coefficient through 100° C (212° F) and then rises slowly. The expansivity of the alloy was materially reduced in comparison to its former state. A comparison between alloy 5 and that of a carbon-molybdenum steel is shown in Plate 14. Between room temperature and 450° C (842° F), the total expansion of alloy 5 is only one-fourth that of the carbon-molybdenum steel.

25. The above annealing treatments are applicable to all types of design without danger of damage and are economically feasible.

26. To find the effect of high temperature and aging, the specimen used for the preceding studies was heated to 1040° C (1900° F) for two hours and quenched in water and then aged for 16 hours at 540° C (1000° F). The effect of this treatment, Plate 15, is to increase the expansivity and approach the conditions of the as forged state. As has been previously mentioned, high temperature treatment increased the grain size and also the expansivity. It is obvious then that any high temperature treatment which would tend to increase grain size should be carefully avoided.

27. Alloy 6 shows the effect of 2 per cent chromium on the base composition of alloy 5. Plate 16 shows the curve is linear up to 175° C and then flattens considerably, exhibiting a nearly zero coefficient between 175° C and 225° C where a sharp break occurs and the curve rises in a straight line. The net effect, however, is to raise the expansivity over that of alloy 5 at the higher temperatures and to lower the inflection point.

28. The expansion specimen was annealed at 700° C for 24 hours and furnace-cooled. In this case differing from alloy 5, no changes in expansion characteristics were noted. The curve resulting from this treatment coincided identically with that of the untreated specimen.

29. The effect of 2 per cent molybdenum on the base composition of alloy 5 is shown by alloy 7, Plate 17. The curve rises slowly with a decreasing slope and, as in alloy 6, approaches a zero coefficient. The effect of the molybdenum on the expansion is to increase the expansivity and to lower the inflection point as compared with alloy 5. It may be noted that the molybdenum has the same effect as chromium in increasing the expansivity and lowering the inflection point.

30. Alloy 9 was an attempt to find the effects of aluminum on the base composition of alloy 5. The addition of 1.95 per cent Al increased the expansion tremendously (Plate 18). The curve presents no inflection point and rises almost linearly. Needless to say, this alloy presents no possibilities as a low expansion alloy.

31. To find the effect of increased percentages of titanium, alloy 10 containing Al - 1.74 per cent, Ti - 0.96 per cent was prepared. This alloy presented a curve, Plate 19, almost identically to that of alloy 9. The curve again is linear and rises with no evidence of an inflection point. As alloy 9, this alloy presents no low expansion possibilities.

32. Kovar exhibits expansion properties as given in Plate 20. The curve is linear until a temperature of 400° C is reached where it undergoes a rapid change in slope and rises rapidly. It is seen that although the alloy has a fairly low average coefficient to 450°, the extreme slope in this vicinity would tend to decrease its usefulness unless a fairly constant temperature can be maintained. This is generally not possible in practice.

33. An attempt to decrease the expansivity by annealing at 700° C for 24 hours proved unsuccessful. The curve resulting from this treatment coincided identically with the first curve.

34. The Invar of composition Fe 64.1 per cent, Ni 30.2 per cent, Co 5.5 per cent, was prepared and the expansion properties studied. The curves plotted on Plate 21 are the results obtained by various heat treatments. The curve in the as received condition has a fairly high expansivity and shows no evidence of a low expansion region. When the specimen was heated to 600° C (1112° F) and quenched in water, a material reduction was obtained in the expansivity. The specimen was then heated at 700° C for 24 hours and furnace-cooled. The curve resulting from this treatment shows a low expansion region which is slightly higher than the "quench curve," but approaches a zero coefficient at 125° C, so that the total expansivity at the higher temperature is lower.

35. To make a comparison of the expansion properties of the iron-nickel and iron-nickel-cobalt alloys with those of a steel now used in high temperature steam work, an expansion specimen was cut from a carbon-molybdenum steam pipe obtained from the New York Navy Yard. The expansion curve, Plate 22, is nearly linear with temperature and has a value of 13.7×10^{-6} per degree C at the elevated temperatures. Plate 14 shows the carbon-molybdenum steel in comparison with alloy 5.

Corrosion Properties

36. The results of the steam corrosion test conducted at 1000° F (540° C) are given in Table 3, and illustrated graphically in Plate 23.

37. The scale formed during the first 340 hours was tightly adherent. This is brought out by the fact that after an additional 752 hours there was no additional increase in weight in the test pieces. Although some of the alloys had a higher initial corrosion than the C-Mo steel or the Bain metal, this corrosion did not increase with time and a steady state was reached. The calculated loss of metal in any case is in the neighborhood of one-thousandth of an inch.

38. As stated before, these alloys contain very little carbon and therefore detrimental effects that may be caused by decarburization are negligible. This is not the case with C-Mo steels which are known to suffer from this cause. However, just what effect steam corrosion has on the physical properties of the low expansion alloys is not known and this study is to be one of the objects of a future report.

39. The atmospheric corrosion results are given in Table 4 and plotted in Plate 24. The corrosion is, in general, lower than in the steam corrosion, although a few alloys; namely, (4), (9) and (10), show a higher oxidization. In addition, it may be noted that the scale was not firmly adherent as indicated by the increased corrosion after the 340 hour period.

Age-Hardening Properties

40. A study was made to determine whether the low expansion alloys were susceptible to age-hardening since the proposed application is in the temperature range in which some ferrous alloys age-harden.

41. A series of specimens from alloys (4), (5), (6), (7), (9) and (10) were heated to 1040° C (1900° F) and an additional set heated to 1200° C (2200° F) for three and two hours, respectively, and quenched in water. The specimens were aged at 425° C (800° F), 540° C (1000° F), and 650° C (1200° F) for various times and the hardness measured. (See Table 5.)

42. The increase of hardness, Rockwell "B", resulting from the 1040° C (1900° F) quench, 425° C (800° F) age was small in alloys (4), (6), and (7), having a maximum increase in hardness from 1 to 3 points. Alloys (5), (9), and (10) have a greater increase with a maximum change of 19, 14, and 15 points, respectively. Aging at 540° C (1000° F) following the 1040° C (1900° F) quench, produced a lower maximum hardness increase and the change occurred in a much shorter time. Again alloys (4), (6), and (7) showed little change in hardness and alloys (5), (9), and (10) showed an increase of 14, 15 and 15 points, respectively. At this temperature, a decrease in hardness was noted after some 8 hours of aging. Aging at 650° C (1200° F) following the 1200° C (2200° F) quench produced a still lower maximum hardness change. The alloys (4), (6), and (7) aged approximately the same as before, and alloys (5), (9), and (10) showed a much smaller change than the 540° C (1000° F) age.

Physical Characteristics

43. As all of the stress-strain curves were very similar in character, only one set of curves will be included in this report. Plates 25 to 29 are typical examples of the curves obtained and show the variation of physical properties with temperature. Young's modulus of elasticity was found graphically. The elastic limit was taken as the point where the slope of the curve departed from that of a straight line. Fortunately this point is well marked in all these alloys.

44. The physical properties of the alloys at 70, 300, 600, 700, and 900° F are given in Table 5, and are plotted on Plates 30 to 38 inclusive.

45. An examination of the curves indicates that values of the modulus do not show very good agreement, but a survey of the literature discloses that this is an extremely difficult quantity to determine precisely. The general form of the curves is similar and differs

FEB 8 - 1940

mainly in the relative values. The modulus curves for the low expansion alloys present an interesting feature in that they differ from ordinary carbon steels; the elastic modulus begins at a high value at room temperature and then decreases through a minimum at a temperature between 300° F to 600° F, depending upon the composition, and then rises to its original value with increasing temperatures. In Plates 7 to 22, the modulus curves are plotted on the same plate as corresponding expansion curves. The practical value of this plot is important in that it enables a calculation of the stress on a section confined in length and heated to various temperatures, from the relation of $S = Ea$, where S = temperature stress, a = total expansion, E = modulus of elasticity at the temperature concerned. This computation permits an evaluation of the alloys in terms of both expansion and physical properties. By considering the ratio of temperature stress to elastic limit, a figure of merit is obtained, for it is seen that whenever the figure of merit exceeds unity the alloy would not be stressed beyond its elastic limit if tightly fixed at both ends and heated to the indicated temperature. This is based on the assumption that elastic limit and elastic modulus are the same in compression as in tension. This assumption is well justified by experience.

46. The values for the temperature stress and figure of merit of the various alloys are given in Tables 7 and 8, and are shown graphically in Plate 39.

47. In considering the physical properties of the Fe-Ni and Fe-Ni-Co alloys, it is seen that the curves are very similar, and, therefore, will not be discussed in detail. However, the effect of the addition of Mo, Cr, Al, and Ti on the properties are of interest. Chromium and molybdenum are known to improve the properties of steel at high temperatures. When molybdenum is added to the Fe-Ni alloy (as in alloys 3 and 4), a decided improvement is noticed in the physical properties as reflected in the tensile strength and elastic limit. However, when either chromium or molybdenum is added to the Fe-Ni-Co alloys (as in alloys 6 and 7), a decrease in physical properties was obtained. The addition of aluminum and titanium has a marked effect on alloys 9 and 10. These alloys show an increase in tensile strength with increasing temperature. As indicated in the age-hardening studies, these alloys have the ability to age and this increase in hardness is reflected in the tensile strength.

48. Upon considering the relative merits of the various low expansion alloys studied in comparison to the carbon-molybdenum steel, alloy 5 containing 29 per cent Ni and 18 per cent Co offers the best combination of properties for use in high temperature steam pipes. This alloy has a low expansion, a low modulus, and a high elastic limit. The temperature stresses produced are low and as seen in Table 8, it has a high figure of merit. The modulus has a value of 13×10^6 psi at 300° F and passes through a minimum of 8×10^6 psi at 500° F and then increases to 35×10^6 at 900° F. In comparison, the modulus of the carbon-molybdenum steel is at 29×10^6 psi at room temperature and decreases fairly rapidly to 7×10^6 psi at 900° F. In the region of 800° F, the operating temperatures for super-heated steam, the modulus is 13×10^6 psi and is the same as that of alloy 5. The tensile values

of alloy 5 are excellent throughout the temperature range. At room temperature, it has an ultimate strength of 101,000 psi coupled with good ductility and as the temperature increases the value decreases to 84,000 psi at 300° F and then increases to 95,000 psi at 800° F. In comparison the carbon-molybdenum steel of the type now used in high temperature steam lines has a fairly constant tensile strength throughout the temperature range, but a lower value of 48,000 psi at 800° F. However, when considering the various physical properties, it is the elastic limit that is of importance in this study, for it is the elastic limit values that determine the figure of merit. The elastic limit values of alloy 5 are about twice as high as those of the carbon-molybdenum steel. The alloy 5 has an elastic limit of 55,000 psi at 300° F and this falls to 47,000 psi at 800° F. The carbon-molybdenum steel has a value 30,000 psi at room temperature which decreases to 17,000 psi at 800° F. Thus, when the values for the elastic limit and temperature stress of the two steels are combined in the figure of merit, it is seen that alloy 5 has a figure of merit of two through 800° F, while that of carbon-molybdenum steel is 0.2 at 800° F. Accordingly, if alloy 5 were confined in length and heated to 800° F, its elastic limit would not be exceeded.

SUMMARY AND CONCLUSIONS

49. Various alloys of iron-nickel and iron-nickel-cobalt with additions of chromium, molybdenum, aluminum and titanium were made. The alloys were studied for expansion, physical and corrosion properties.

50. The addition of chromium, molybdenum, aluminum and titanium raised the expansivity of the base composition. Aluminum and titanium rendered the alloy useless for low expansion work.

51. A series of heat treatments showed that a material reduction in expansion could be obtained by annealing at 700° C or for a long time (348 hours) at 500° C.

52. Heating the alloys to temperatures high enough to promote grain growth impairs the low expansion properties.

53. Alloy 5 (28 per cent Ni, 18 per cent Co), after an annealing treatment, had a mean coefficient of expansion one-fourth that of carbon-molybdenum steel at 800° F.

54. A study of age-hardening properties revealed that, with the exception of alloys 9 and 10, little increase in hardness could be expected. Alloys 9 and 10 aged as a result of the aluminum and titanium content.

55. The corrosion resistance of the alloys was good and in the steam corrosion tests compared favorably with those of carbon-molybdenum steels. The scale formed was very adherent and there was no evidence of increased corrosion after the initial 348 hours.

56. A new design extensometer was constructed which enabled the measurement of moduli at elevated temperatures. The results obtained were about as accurate as room temperature results with ordinary extensometers.

57. The low expansion alloys, in general, exhibited higher tensile strengths and elastic limits than the carbon-molybdenum steels.

58. Additions of molybdenum improved the physical properties of the iron-nickel alloys. These additions also exerted a stabilizing action on these properties at elevated temperatures.

59. Additions of chromium and molybdenum lowered the physical properties of the iron-nickel-cobalt alloys. However, a stabilizing effect was evident at higher temperatures.

60. Alloys 5 (28.0 per cent Ni, 18 per cent Co) and 6 (27.0 per cent Ni, 17 per cent Co, 2 per cent Cr) presented the best possibilities for high temperature-low expansion work for the alloys studied. Alloy 5 had a very good combination of low expansion, low modulus and high elastic limit at elevated temperatures.

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FEB 8 - 1940

Table 1

Composition of Alloys

(By chemical analysis)

Alloy	Fe	Ni	Co	Ti	C	Mo	Cr	Al
2	60.8	39.00		0.20				
3	59.2	38.95		0.13	0.025	1.7		
4	57.17	38.70			0.07	3.9		
5	54.3	27.20	18.0	0.31	0.01			
6	53.3	27.40	17.2	0.30	0.02		2.0	
7	53.6	27.2	17.33	0.35	0.02	1.5		
9	52.9	26.17	18.60	0.22				1.95
10	53.9	26.00	17.20	0.96				1.74
Invar	64.1	30.2	5.5	–	0.015			
Kovar	54	29	17 – (nominal values)					

C-Mo steel – C, 0.22; Mn, 0.47; Si, 0.18; Mo, 0.50.

Bain metal – C, 0.14; Mn, 0.49; Si, 0.49; Mo, 0.70; Cr, 1.81.

Co analysis – Co, 98.75%; Ca, 0.22%; C, 0.08%; Mn 0.06%.

Ni, 0.18%; S, 0.02%; Si, 0.08%; Fe, 0.19%.

Table 2

Value of the Average Coefficient

of Expansion to Temperature Indicated

Alloy No.	x 10^6 per ° C		x 10^6 per ° F	
	to 450° C	to 550° C	to 842° F	to 1022° F
2	5.6	7.3	3.0	4.1
3	6.7	8.3	3.7	4.1
4	9.88	–	5.49	–
5[a]	6.8	6.8	3.8	3.8
5[b]	6.0	7.6	3.3	4.2
5[c]	4.4	6.4	2.4	3.6
5[d]	3.6	5.7	2.0	3.2
5[e]	5.7	6.5	3.1	3.6
6	5.4	7.1	3.0	3.9
7	6.0	7.4	3.3	4.1
9	10.6	10.6	5.9	5.9
10	10.6	10.6	5.9	5.9
Kovar	5.7	8.2	3.2	4.5
C-Mo	13.7	13.7		

a – As forged.

b – Annealed at 600° C.

c – Annealed at 700° C.

d – Annealed at 540° C for 348 hours.

e – Heated to 1050° C and quenched in water.

Table 3

Steam Corrosion of Alloys

(Temperature - 1000° F (540° C))

Alloy No.	Gain in Weight - Grams per Square Meter		
	348 hours	752 hours	1100 hours
2	62.6		66.0
3	61.4		61.4
4	79.5		79.5
5	74.0		76.2
6	46.7		46.7
7	30.8		30.8
9	85.2		85.4
10	67.0		67.0
C-Mo Steel	–	44.2	44.4
Bain Metal	–	60.2	59.2

Table 4

Atmospheric Corrosion

(Temperature - 1000° F (540° C))

Alloy No.	Gain in Weight - Grams per Square Meter		
	348 hours	752 hours	1100 hours
2	27.3		43.2
3	77.4		77.4
4	54.6		81.1
5	45.6		45.6
6	38.7		38.7
7	38.7		38.7
9	68.1		88.2
10	59.2		59.2
C-Mo Steel		25.1	25.1
Bain Metal		11.4	11.4

8 - 1940

Table 5

Aging Properties

Treatment – Heated at 1040° C (1900° F) for 45 minutes and water quenched.
Aging temperature – 425° C (900° F)

Hardness – Rockwell B

Alloy	As Quenched	Aging Time in Hours 1/2	1-1/4	2	6
4	77	78	80	80	80
5	87	99	99	98	106
6	77	78	80	80	80
7	83	84	84	84	84
9	103	116	116	117	117
10	106	120	120	121	121

Treatment – Heated at 1040° C (1900° F) for 3 hours and water quenched.
Aging temperature – 540° C (1000° F)

Hardness – Rockwell B

Alloy	As Quenched	Aging Time in Hours 1/4	1/2	1	2	4	8	28
4	75	78	78	79	79	79	80	80
5	88	99	99	102	102	102	102	100
6	77	79	79	78	79	79	79	81
7	80	84	84	84	84	84	84	84
9	102	115	116	116	110	117	114	116
10	104	119	119	119	119	119	119	118

Treatment – Heated at 1200° C (2200° F) for 2 hours and water quenched.
Aging temperature – 650° C (1200° F)

Hardness – Rockwell B

Alloy	As Quenched	Aging Time in Hours 1/4	1	3	23
4	74	77	77	77	79
5	92	99	101	97	97
6	75	78	77	77	79
7	77	82	81	82	81
9	102	110	110	110	108
10	103	113	114	113	112

Table 6

Physical Properties

Temp. °F	Test	Alloy 2	3	4	5	6	7	9	10	C-Mo Steel
70°	Ultimate tensile strength	62140	71240	87880	101400	75000	78000	139000	144000	58500
	Elastic modulus	25×10^6	24×10^6	32×10^6	–	19×10^6	25×10^6	–	–	29×10^6
	Elastic limit	32500	30000	42500	–	37000	37000	–	–	28500
	Elongation %	29.6	30.5	20.2	21.8	22.5	34.3	12.5	12.5	20.3
300°	Ultimate tensile strength	44500	61400	71900	83700	56900	65000	141400	141000	52300
	Elastic modulus	23×10^6	13×10^6	26×10^6	13×10^6	12×10^6	19×10^6	13×10^6	15×10^6	30×10^6
	Elastic limit	20000	29000	27500	55000	31500	37000	115000	58000	28000
	Ultimate elongation	21.8	31.6	23.4	14.0	26.5	21.9	11.7	9.4	31.2
600°	Ultimate tensile strength	40600	61000	75000	86000	54000	54600	140000	159500	55900

Table 6 (continued)

Temp °F	Test	Alloy 2	3	4	5	6	7	9	10	C-Mo Steel
600° (cont'd)	Elastic modulus	8×10^6	18×10^6	29×10^6	17×10^6	11×10^6	–	13×10^6	19×10^6	17×10^6
	Elastic limit	14200	24500	28500	42500	31000	30000	37500	45000	21000
	Ultimate elongation	31.0	32.8	19.5	10.9	19.5	28.6	10.1	8.1	22.7
800°	Ultimate tensile strength	33200	54600	71500	95000	50800	55300	155400	171200	47600
	Elastic modulus	16×10^6	11×10^6	31×10^6	16×10^6	29×10^6	28×10^6	28×10^6	38×10^6	13×10^6
	Elastic limit	14500	17700	2 7500	37500	33000	20000	22500	35000	16700
	Ultimate elongation %	17.3	26.4	13.5	10.7	16.6	18.5	2.65	2.65	20.3
900°	Ultimate tensile strength	26600	54000	68300	70700	45500	49700	133900	–	45500
	Elastic modulus	15×10^6	19×10^6	41×10^6	34×10^6	33×10^6	31×10^6	17×10^6	–	7.0×10^6
	Elastic limit	11500	19500	27500	28000	25000	19500	13000	–	15600
	Ultimate elongation %	–	25.0	21.8	2.92	25.0	17.7	13.3	–	20.3

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Table 7

Temperature Stresses

Calculated from formula S = Ea

Where S = temperature stress,

a = total expansion to upper temperature,

E = modulus of elasticity at upper temperature.

This the stress in pounds per square inch produced when a section is confined in length and heated to temperatured indicated.

Alloy	300° F	600° F	800° F	900° F
2	4660	5625	34100	43700 **
3	6000	23600	29100	66750 **
4	13800	51200	108000	217000 **
5	2600	11000	18000	68000 *
6	4880	9000	32000 *	95600 **
7	8050	–	65200 **	95400 **
9	15300	37800	119500 *	86700 *
10	21000	57300 *	167500 **	–
C-Mo	46800 *	65400 **	71500 **	43100 **

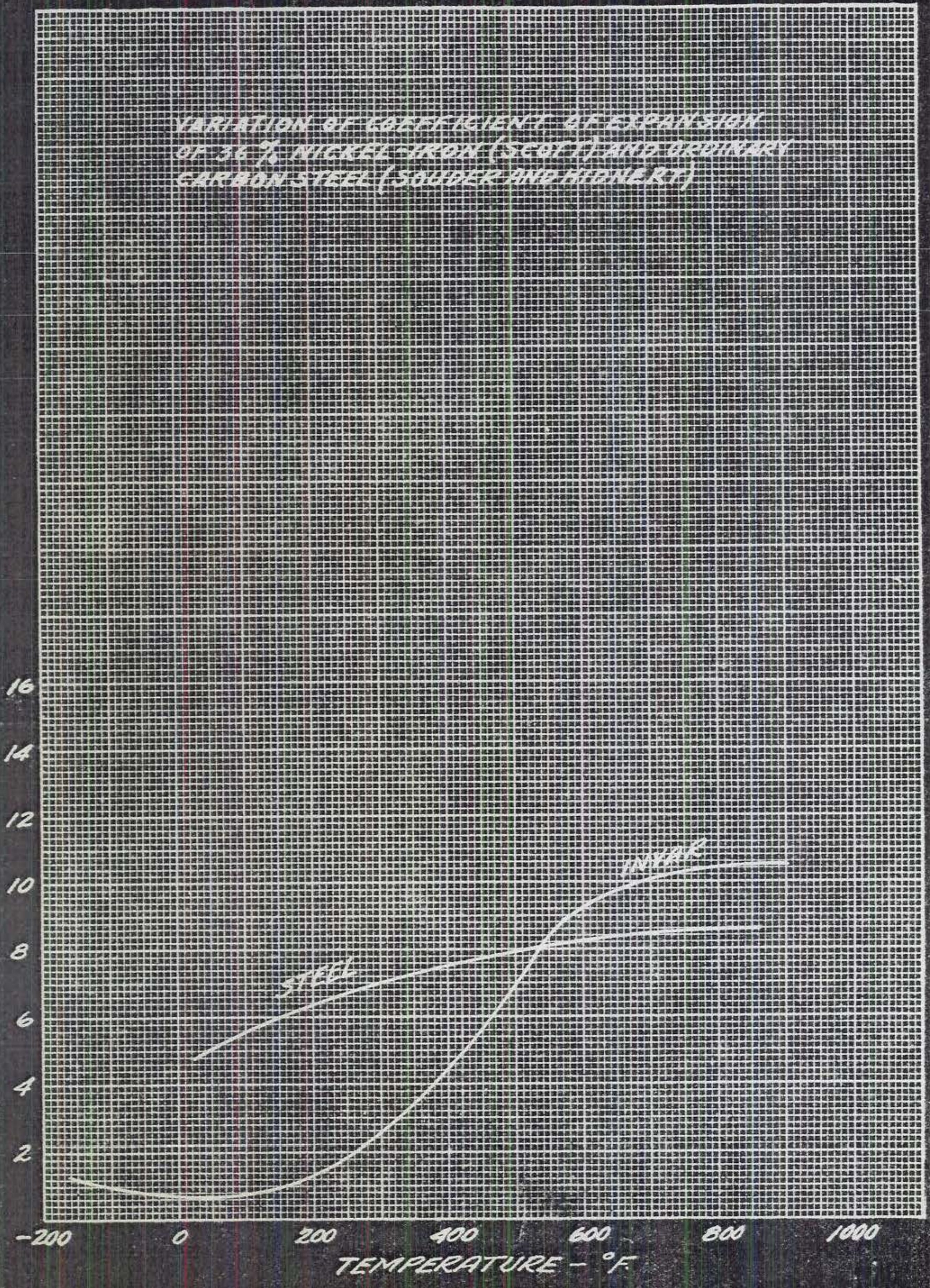
* Value exceeds elastic limit. ** Value exceeds ultimate tensile strength.

Table 8

Figure of Merit

$$f = \frac{\text{elastic limit}}{\text{temperature stress}}$$

Alloy	300° F	600° F	800° F	900° F
2	4.4	2.5	0.43	0.26
3	4.8	1.04	0.60	0.29
4	2.0	0.55	0.25	0.13
5	21.2	3.86	2.08	0.41
6	6.5	3.44	1.03	0.25
7	4.6	–	0.31	0.20
9	7.5	0.99	0.21	0.15
10	2.7	0.79	0.21	–
C-Mo	0.60	0.32	0.23	0.36


VARIATION OF COEFFICIENT OF EXPANSION
OF 36 % NICKEL-IRON (SCOTT) AND ORDINARY
CARBON STEEL (SOUDER AND HIDNERT)
16
14
12
10
8
6
4
2
-200
0
200
400
600
800
1000
TEMPERATURE - °F
INVAR
STEEL


EXPANSION CURVE OF INVAR (SCOTT)
AND CARBON STEEL (SOUDER AND HIDNERT)
STEEL
INVAR
EXPANSION IN THOUSANDTHS
0
1
2
3
4
5
6
200
400
600
800
1000
TEMPERATURE - °F.

PLATE 2

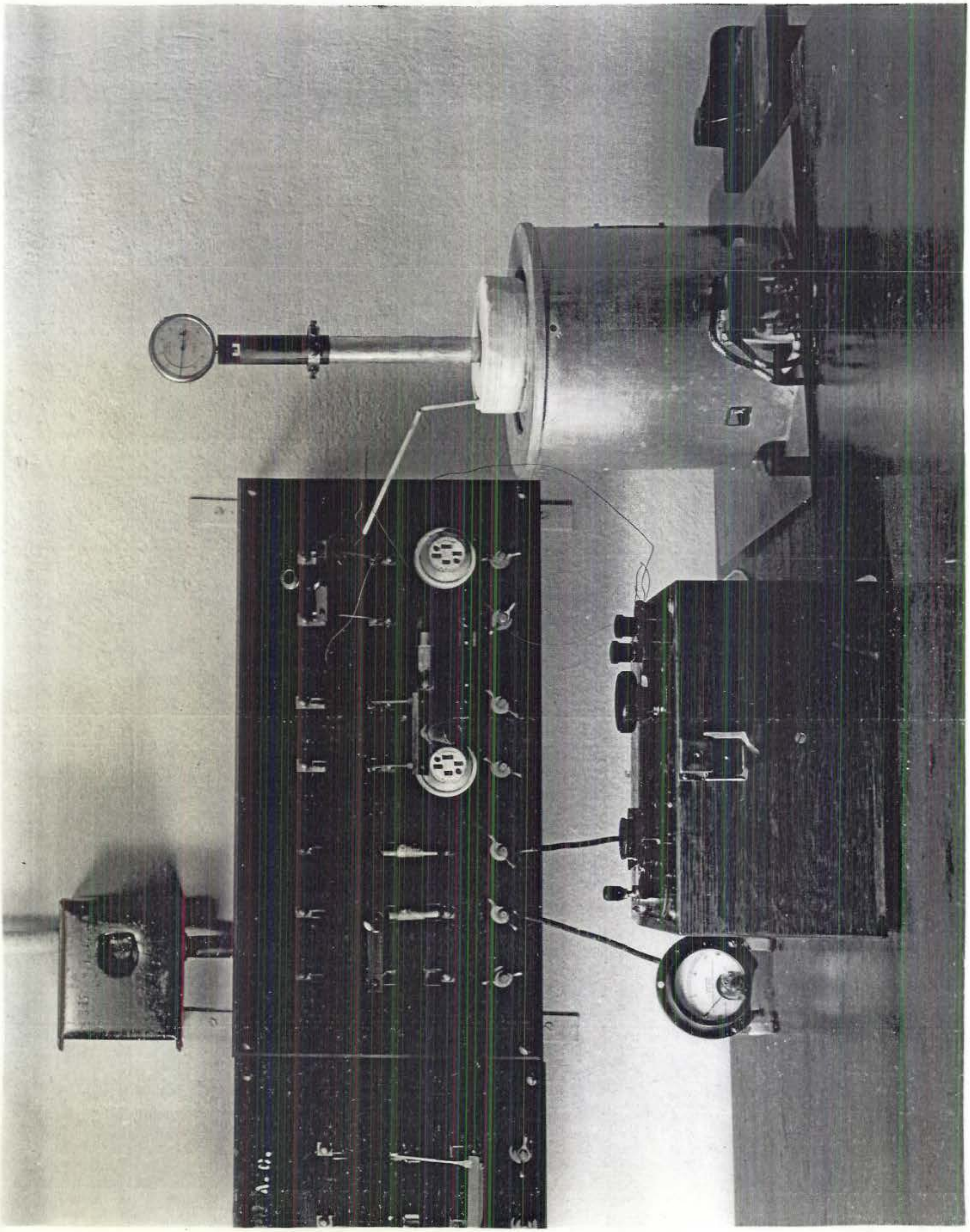


Plate 4

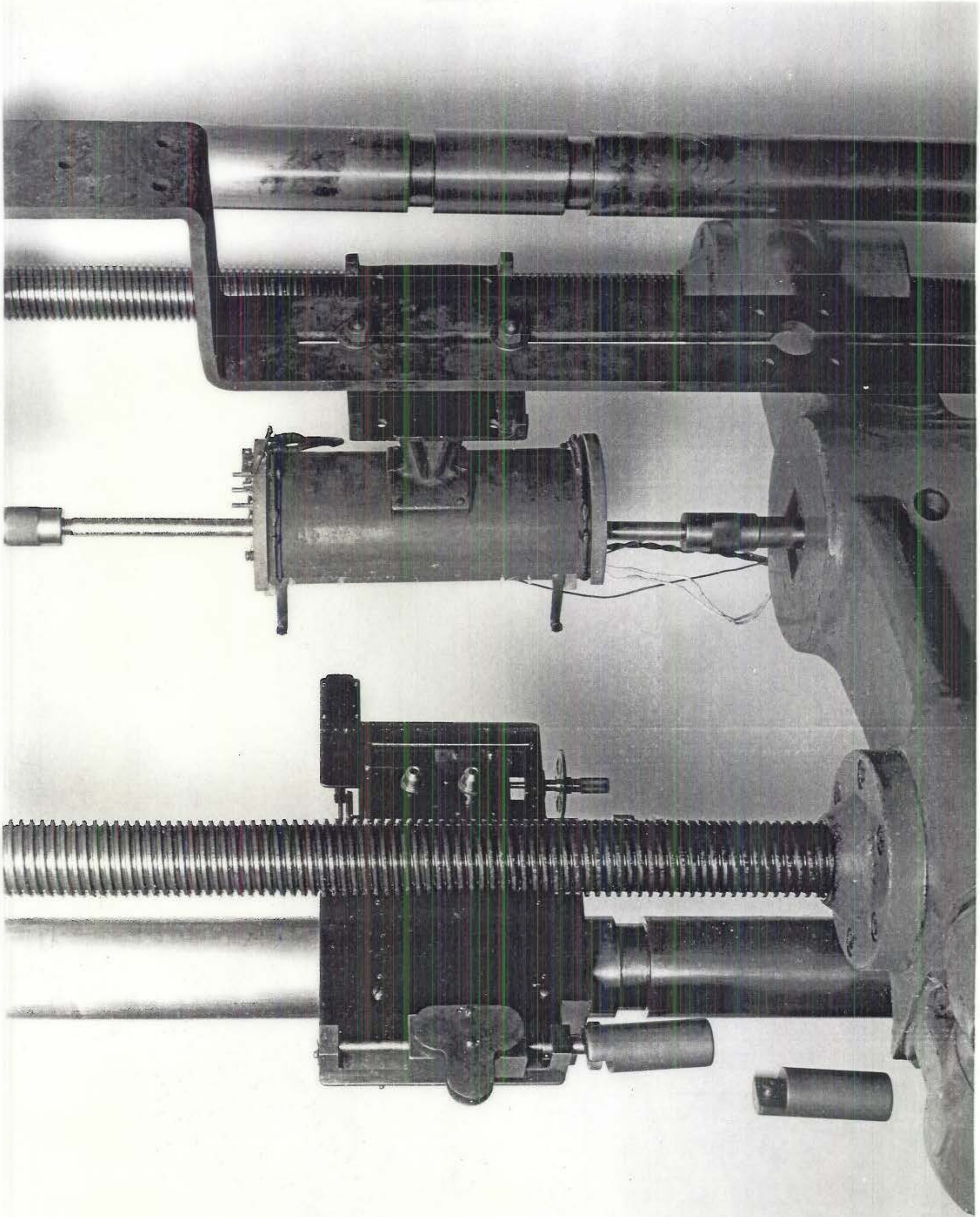


Plate 5

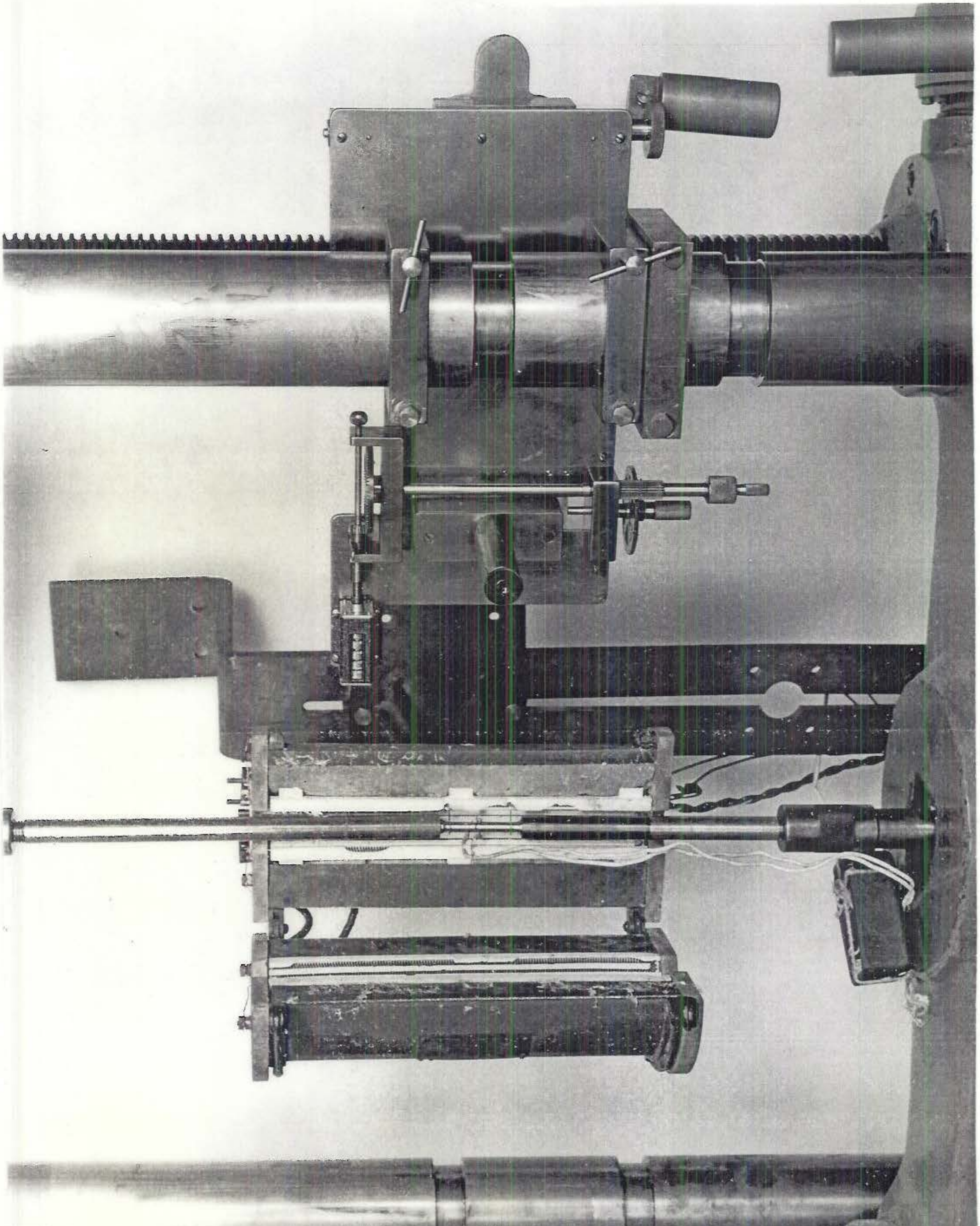


Plate 6

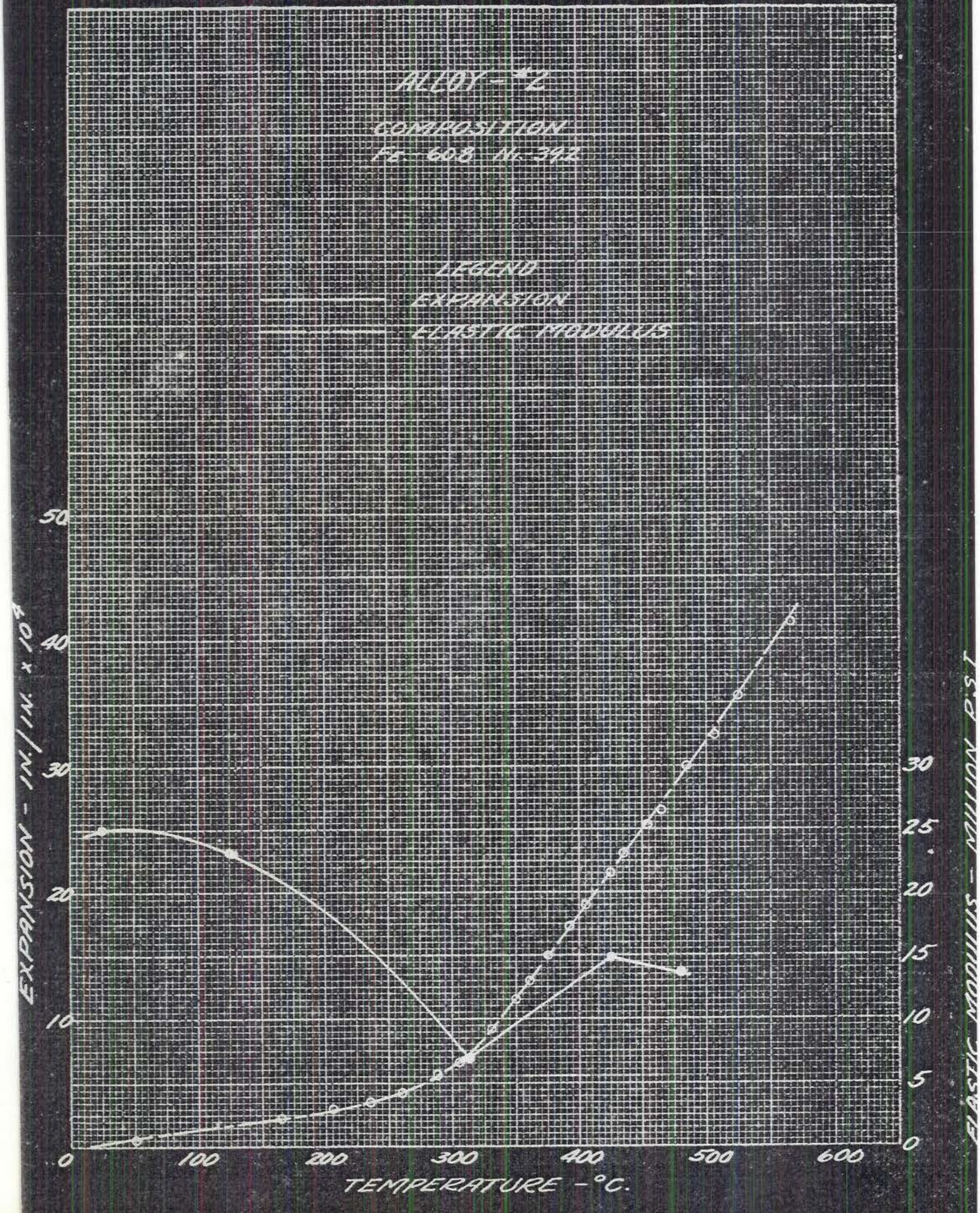

ALLOY - #2
COMPOSITION
Fe 60.8 Ni 39.2
LEGEND
EXPANSION
ELASTIC MODULUS
EXPANSION - IN./IN. x 10⁴
10
20
30
40
50
ELASTIC MODULUS - MILLION P.S.I.
0
5
10
15
20
25
30
0
100
200
300
400
500
600
TEMPERATURE - °C.

PLATE 7

BELLEVUE, D.C. DATE

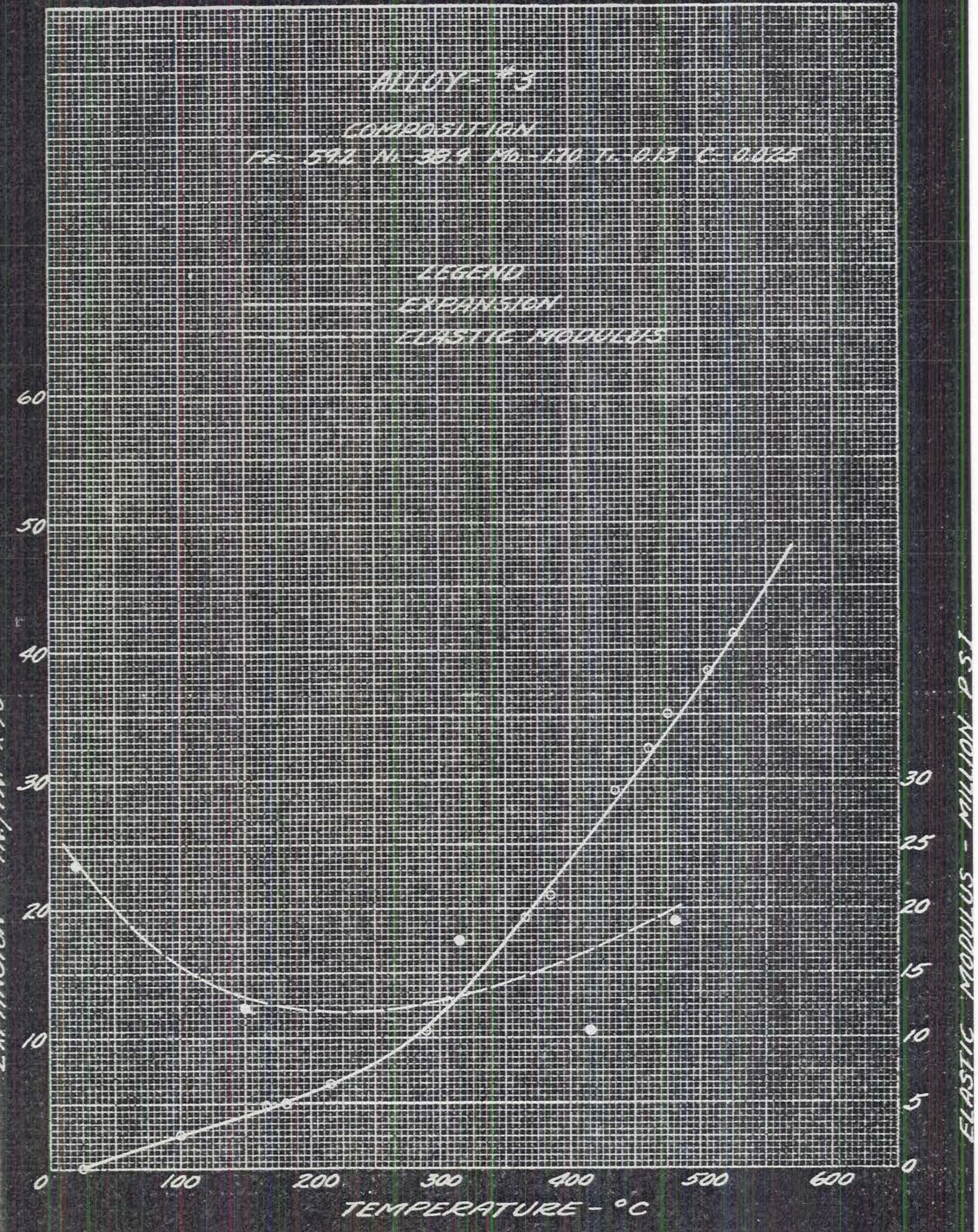
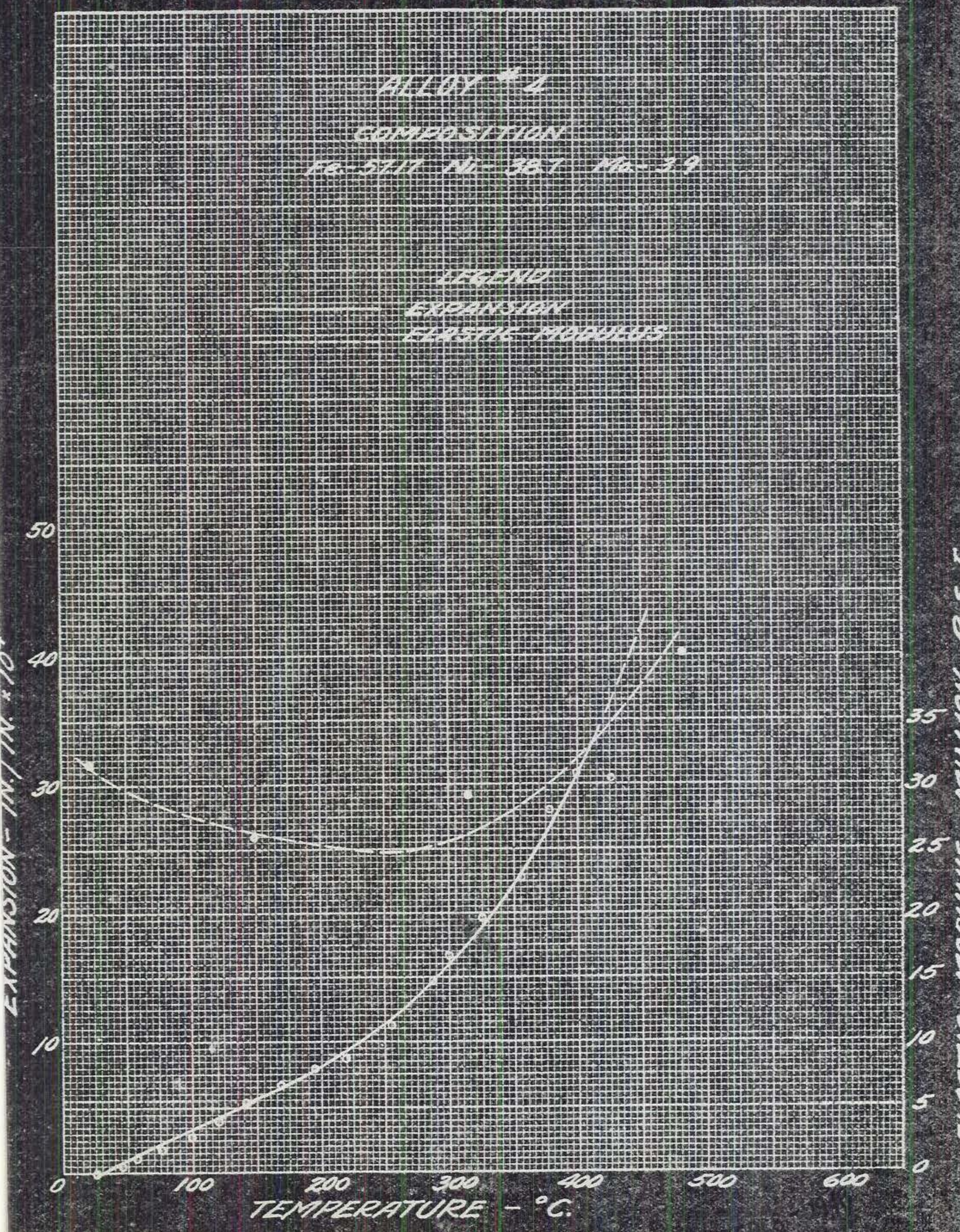


PLATE 8

BELLEVUE, D. C.

DATE



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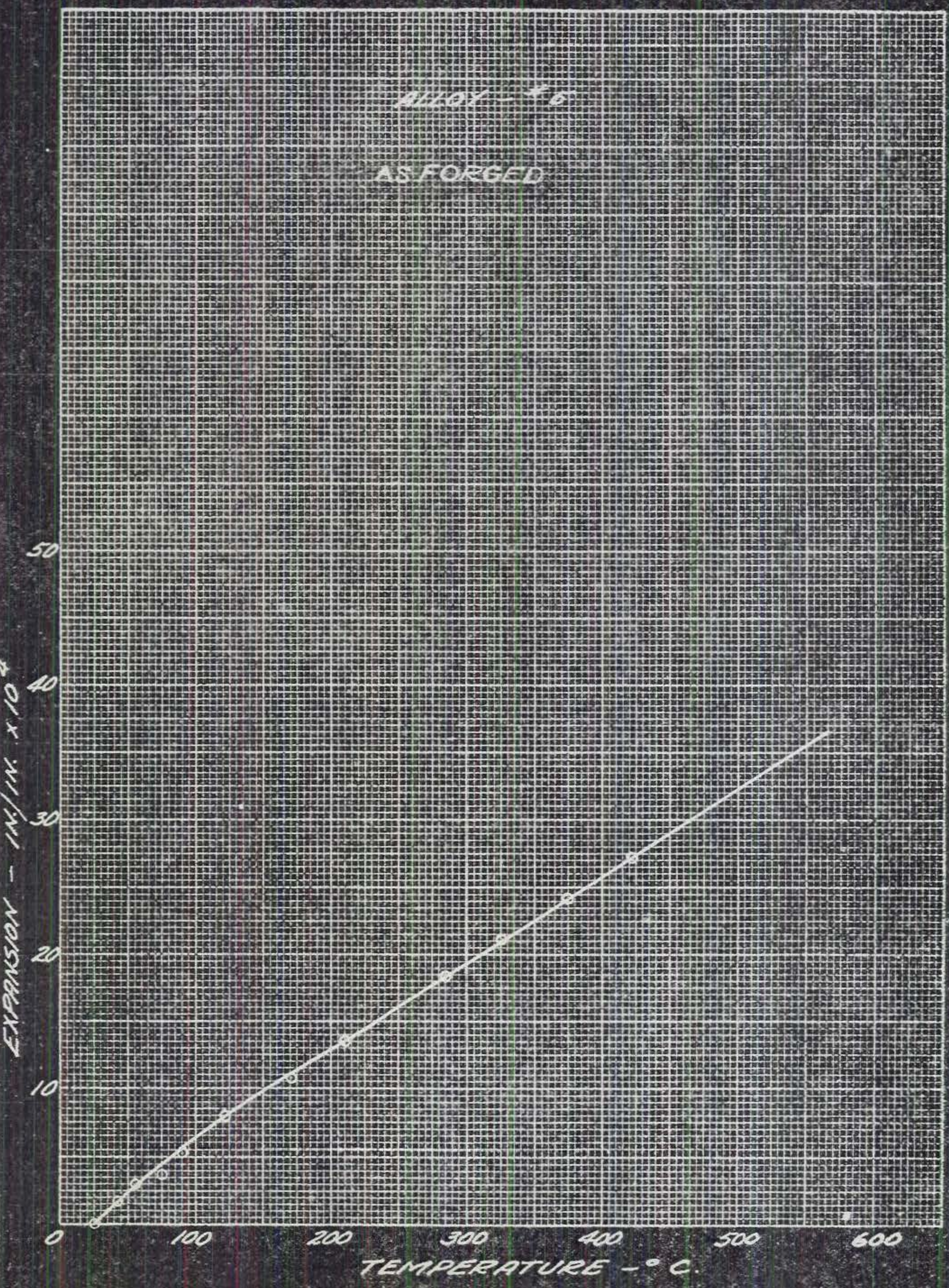

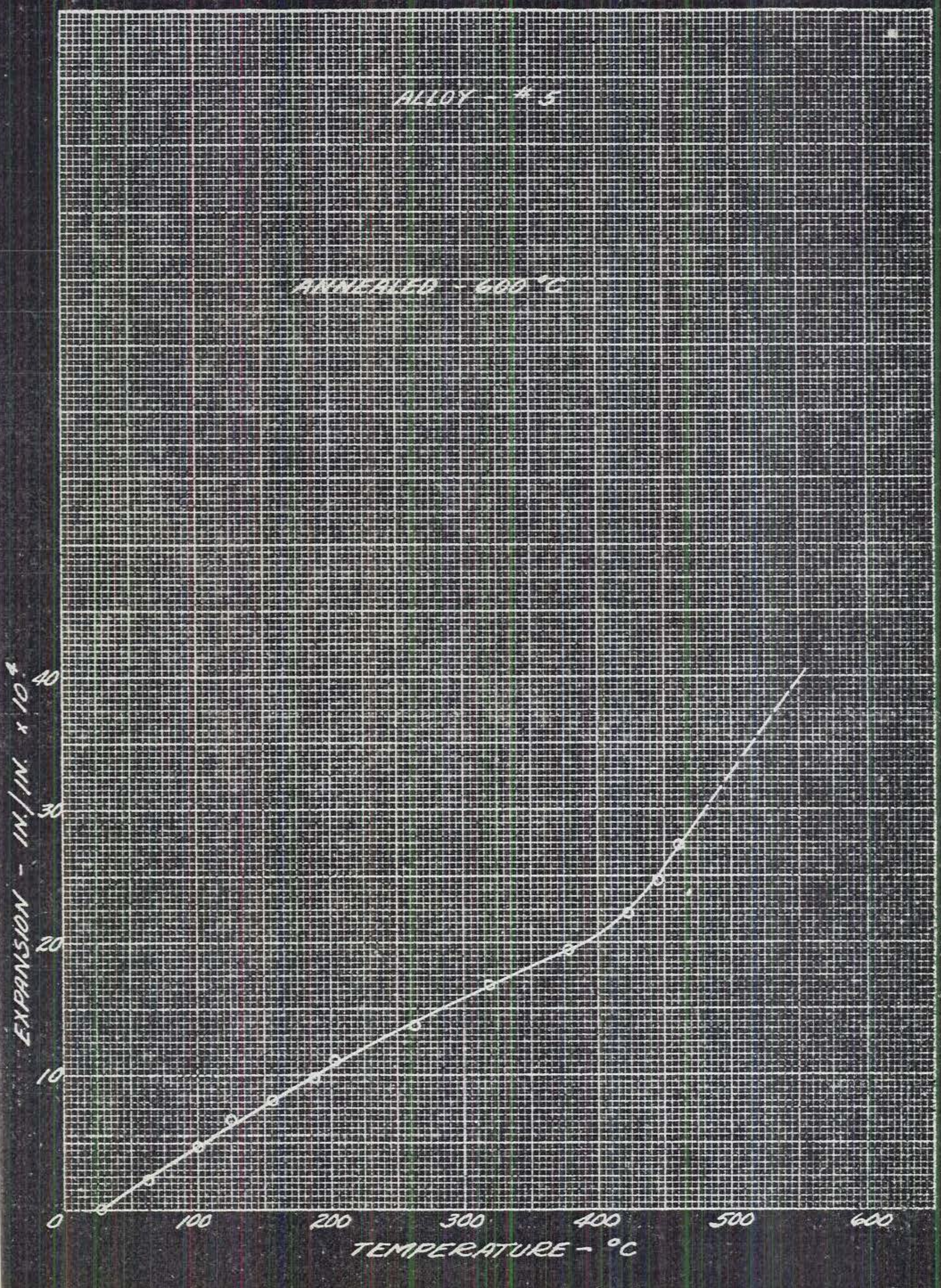
ALLOY - #5
ANNEALED - 600°C
EXPANSION - IN./IN. × 10⁻⁴
0
10
20
30
40
100
200
300
400
500
600
TEMPERATURE - °C

PLATE 11

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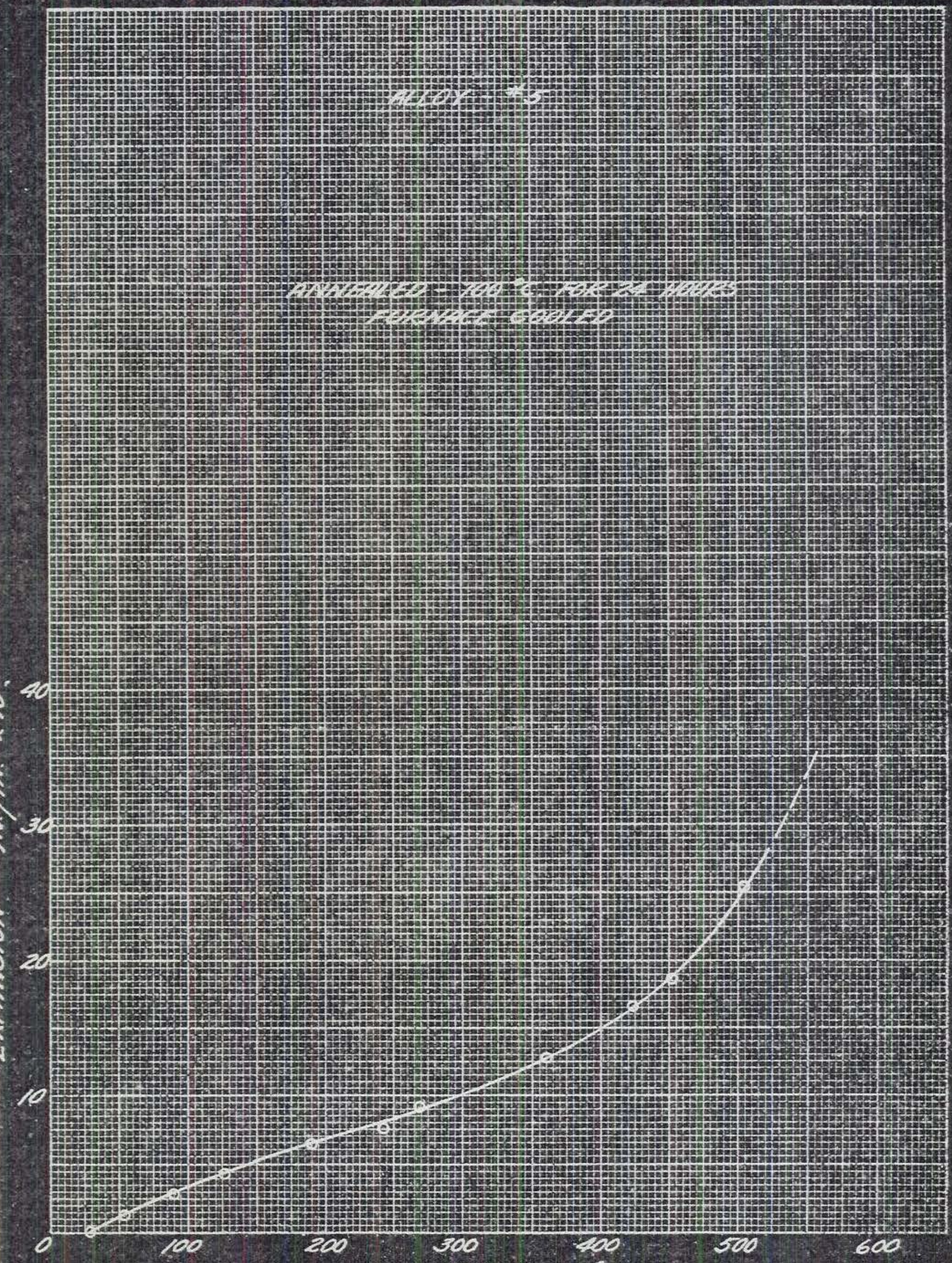

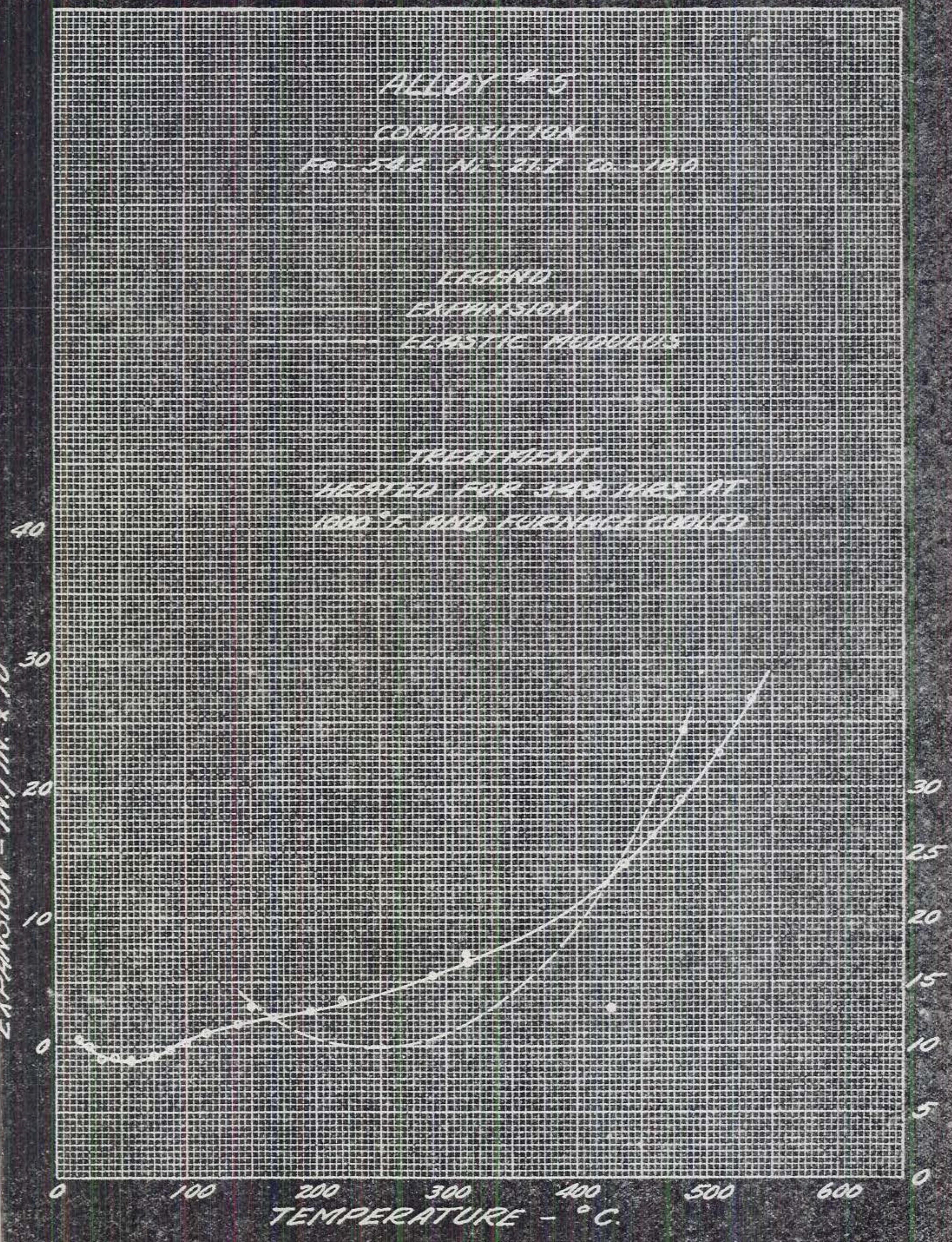
ALLOY # 5
COMPOSITION
Fe-54.2 Ni-27.7 Co-18.0
LEGEND
EXPANSION
ELASTIC MODULUS
TREATMENT
HEATED FOR 348 HRS AT
1000°F AND FURNACE COOLED
EXPANSION - IN./IN. x 10⁻⁴
0
10
20
30
40
ELASTIC MODULUS - MILLION P.S.I.
0
5
10
15
20
25
30
0
100
200
300
400
500
600
TEMPERATURE - °C.

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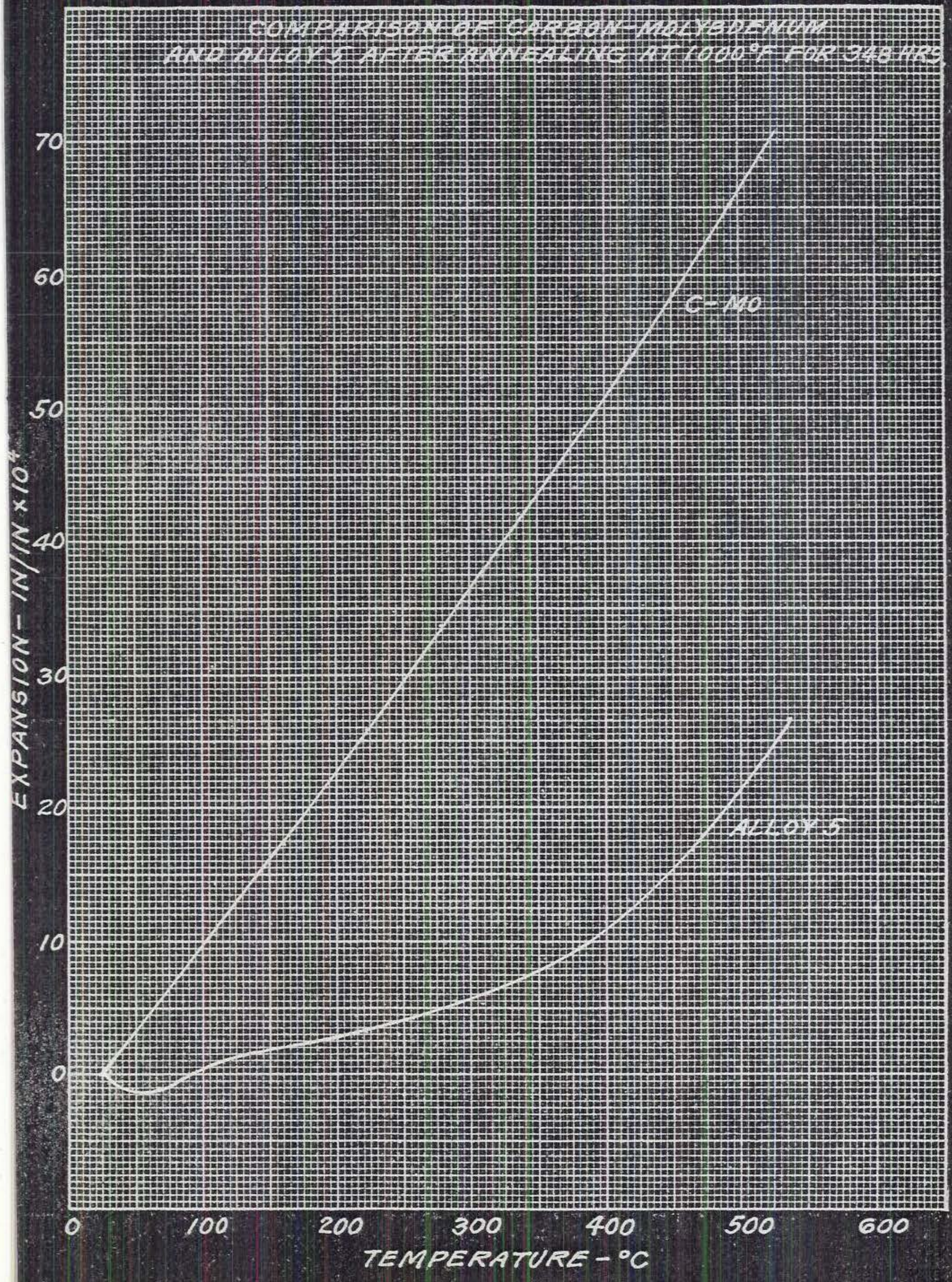

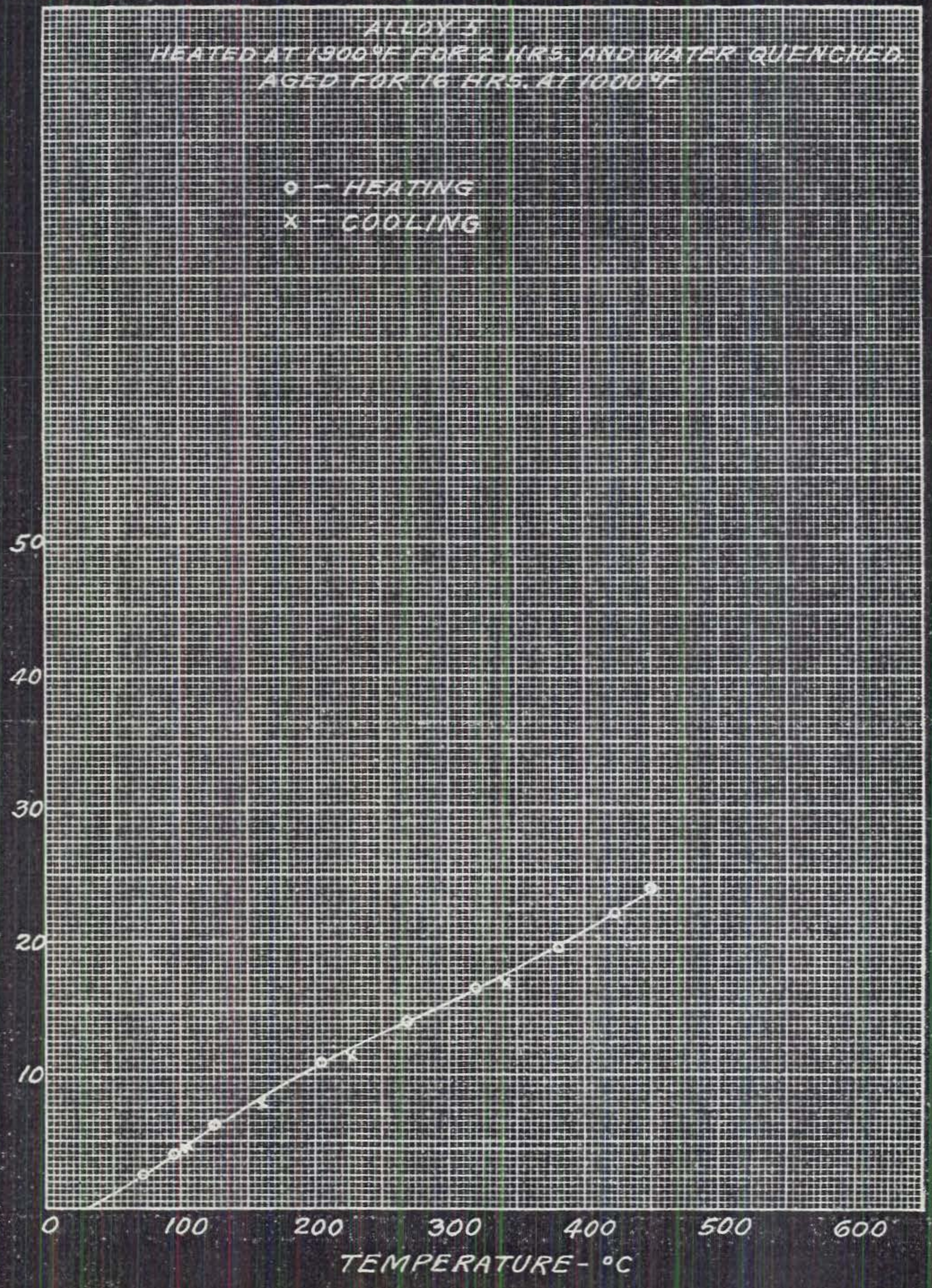
ALLOY 5
HEATED AT 1900°F FOR 2 HRS. AND WATER QUENCHED.
AGED FOR 16 HRS. AT 1000°F
o - HEATING
x - COOLING
50
40
30
20
10
0
100
200
300
400
500
600
TEMPERATURE - °C

PLATE 15

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.
DATE

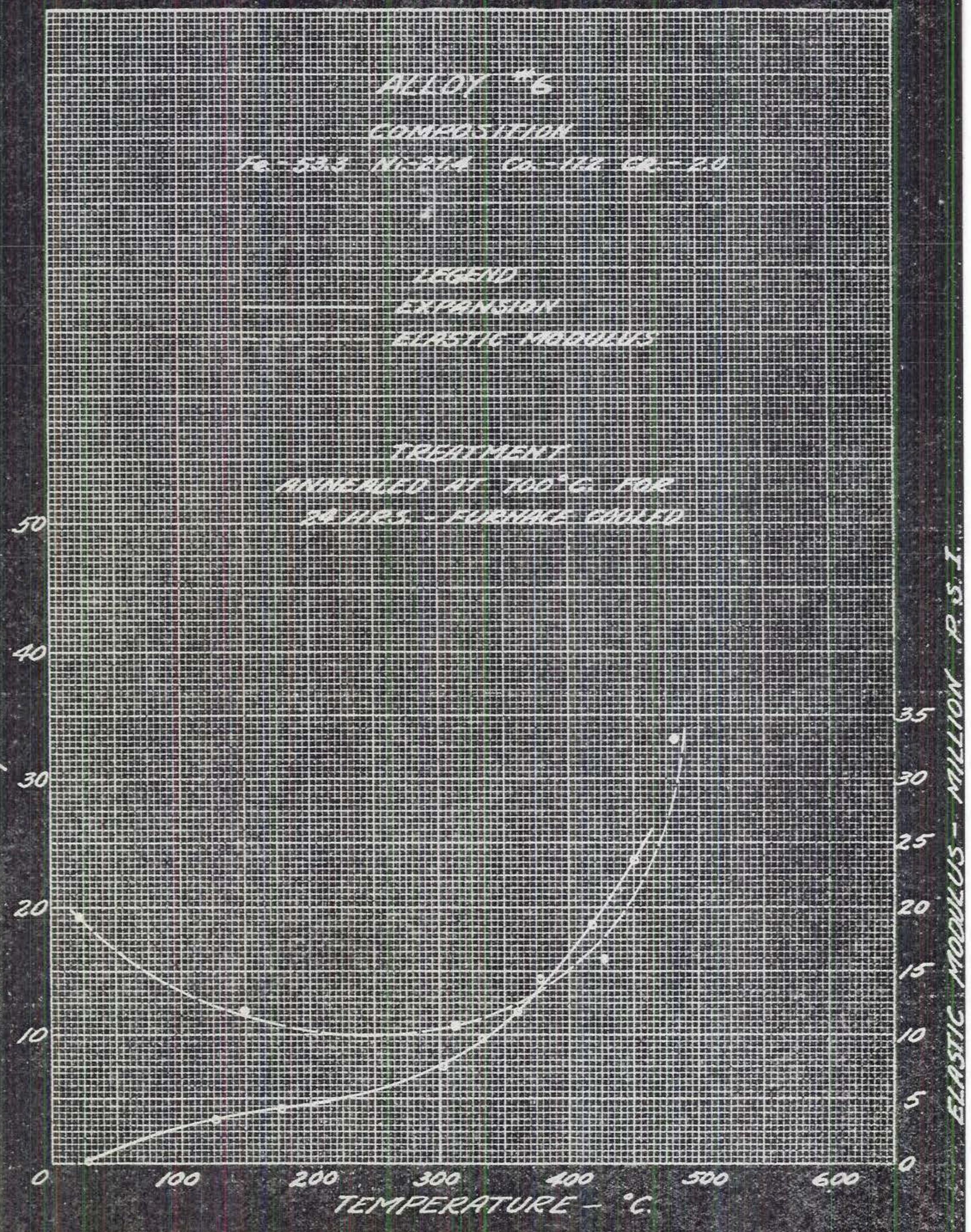

PLATE 16

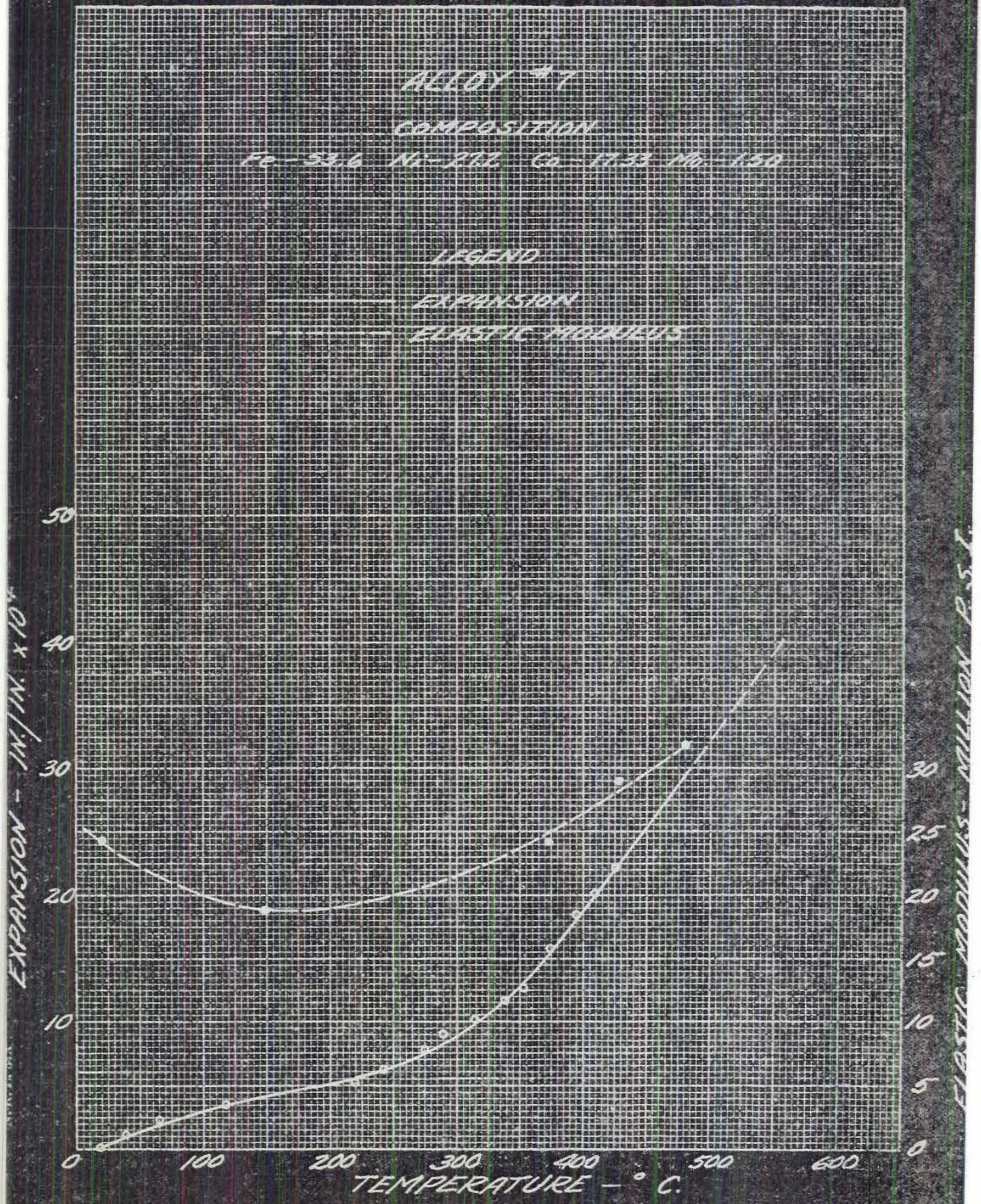
ALLOY #7
COMPOSITION
Fe-53.6 Ni-27.2 Co-17.33 Mo-1.50
LEGEND
EXPANSION
ELASTIC MODULUS
EXPANSION - IN./IN. x 10⁴
ELASTIC MODULUS - MILLION P.S.I.
TEMPERATURE - ° C.
0
100
200
300
400
500
600
10
20
30
40
50
5
15
25

PLATE 17

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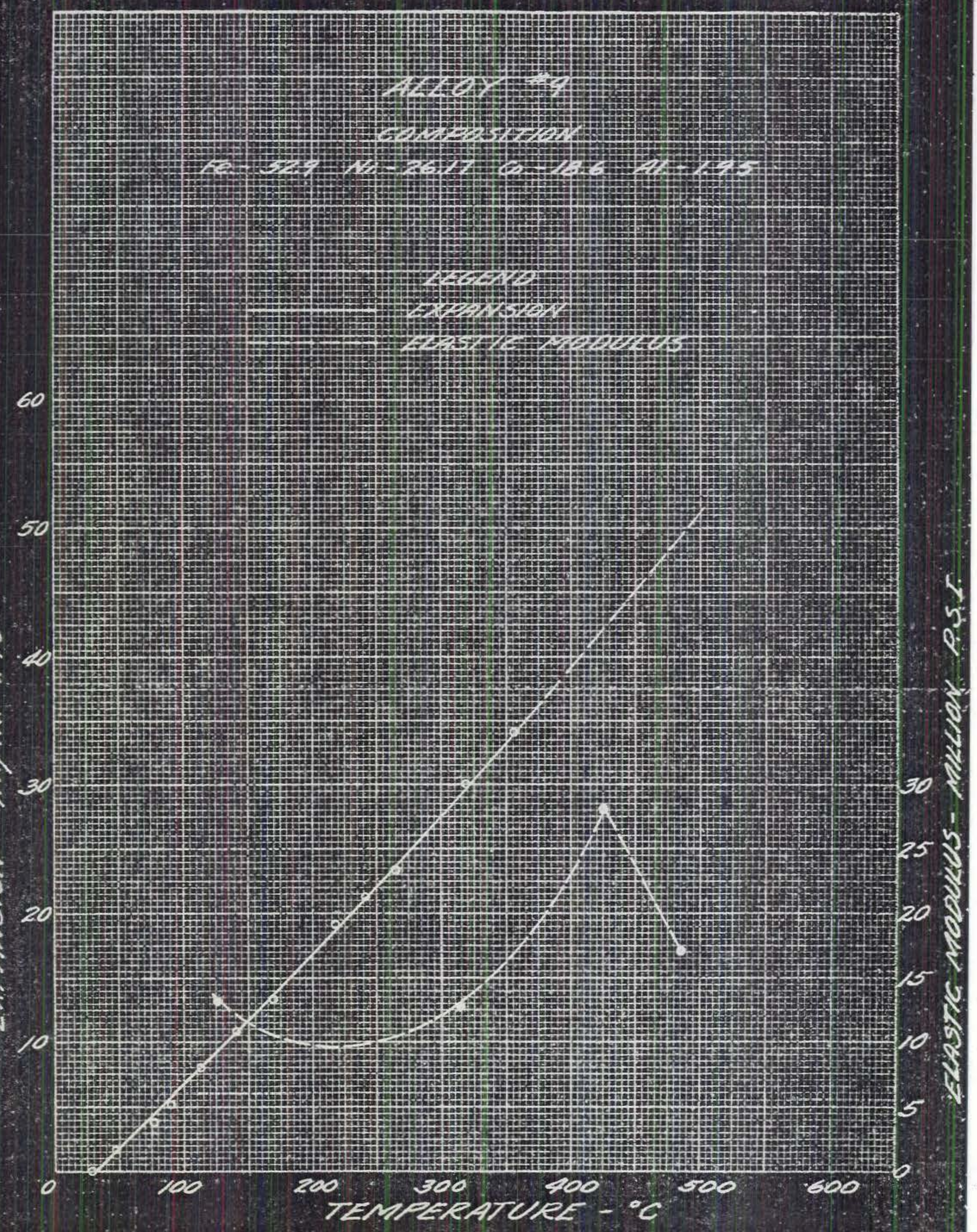

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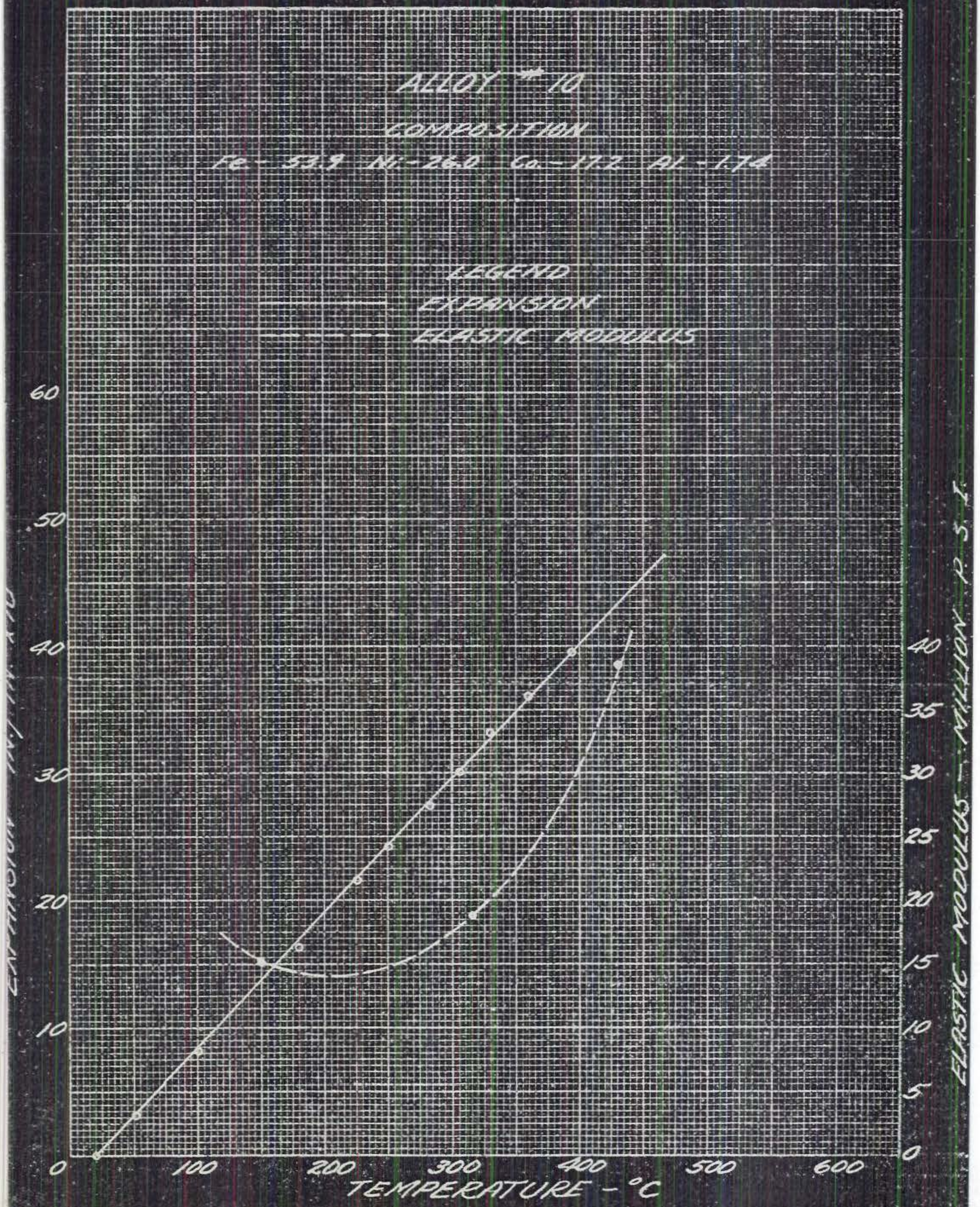

PLATE 19

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DATE

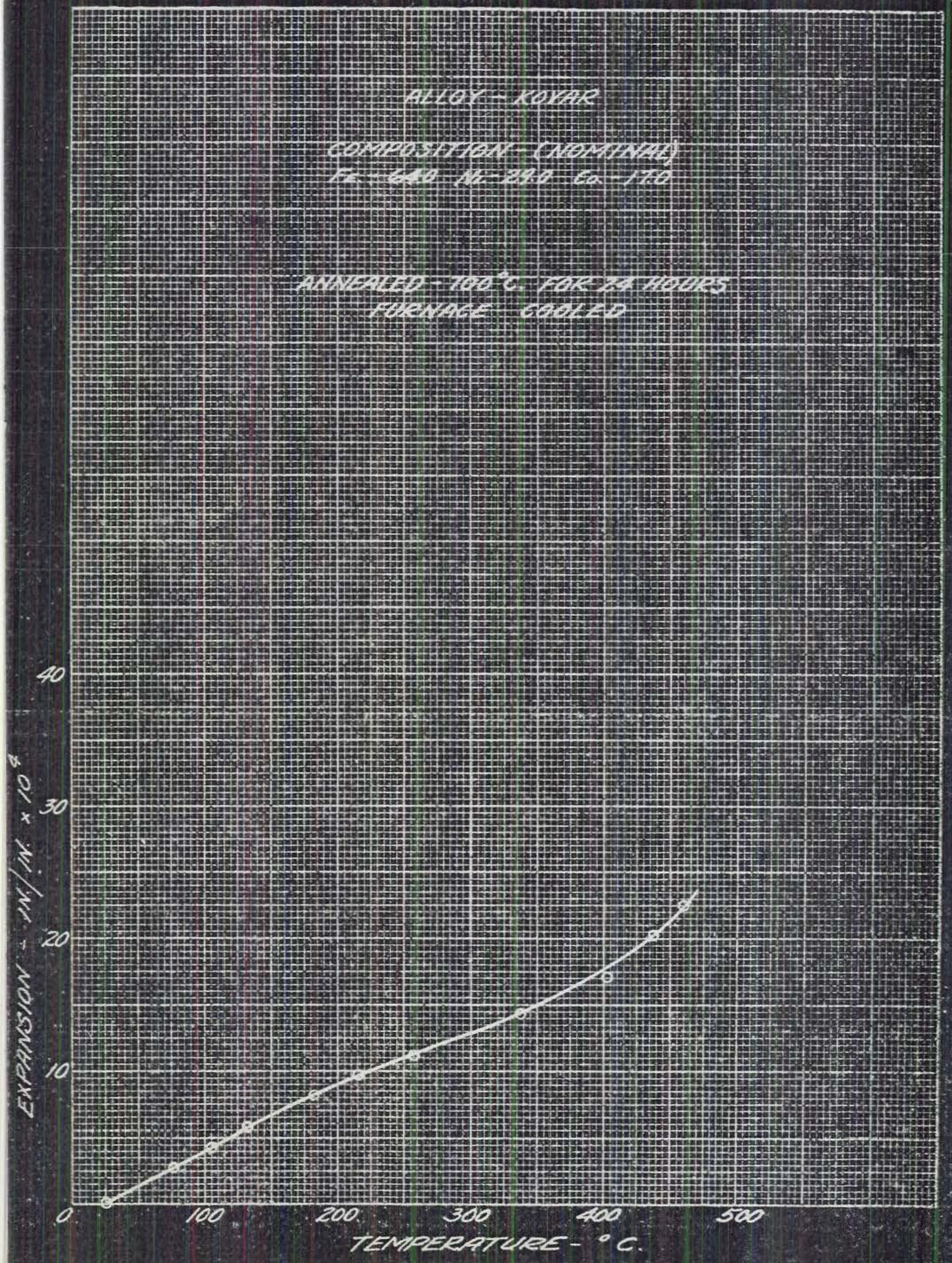

PLATE-20

BELLEVUE, D. C.

DATE

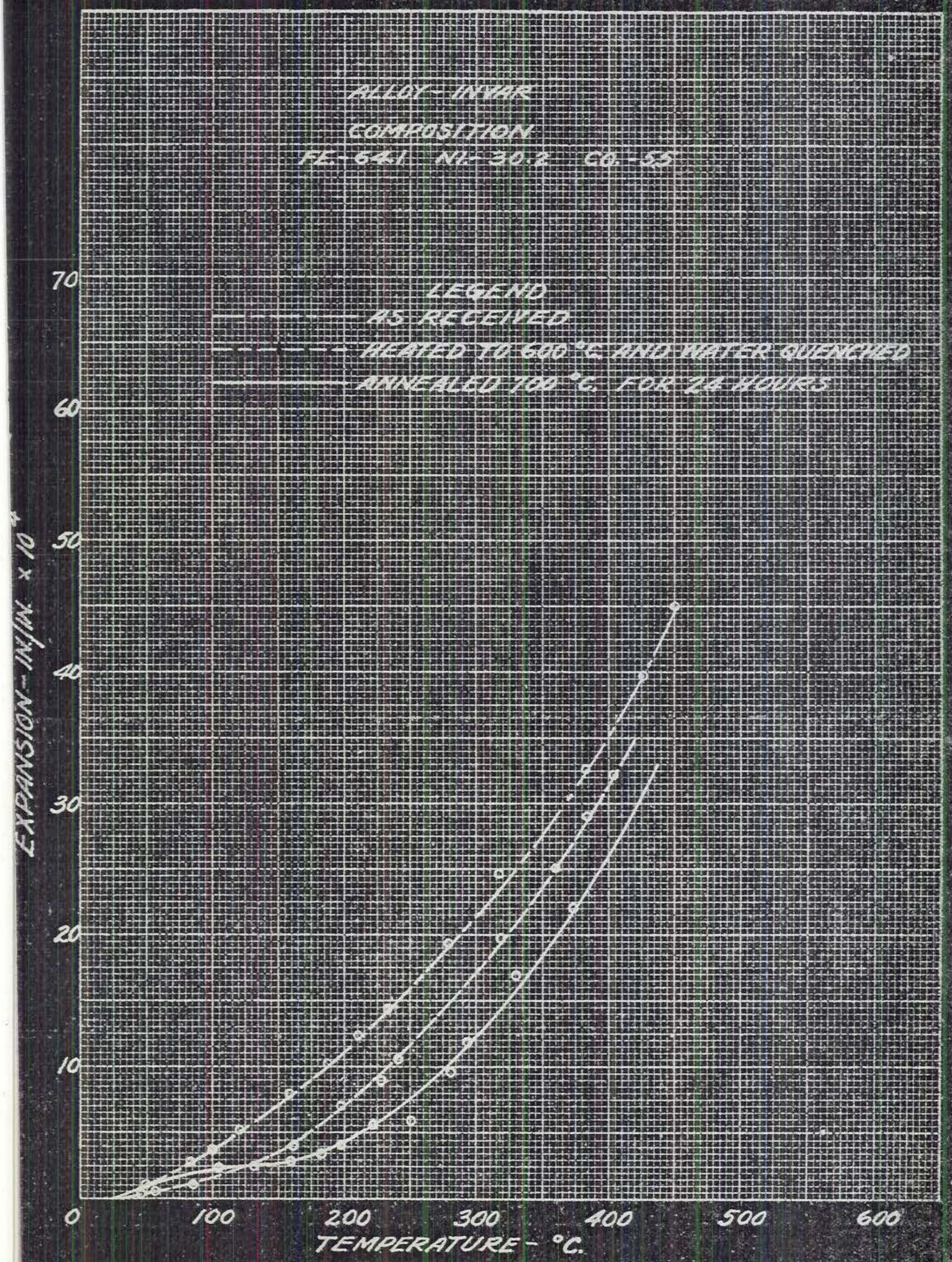

PLATE 21

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DATE

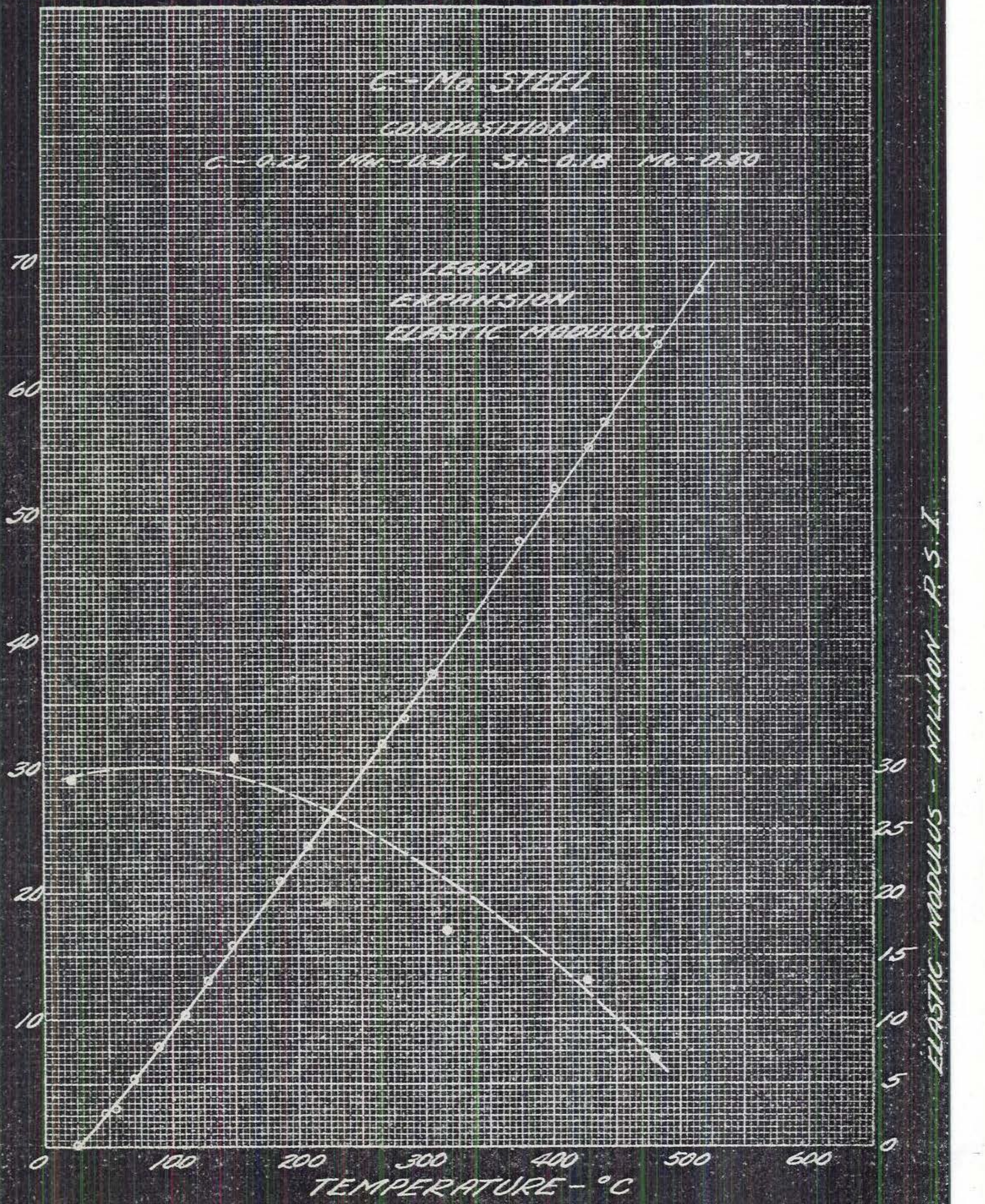
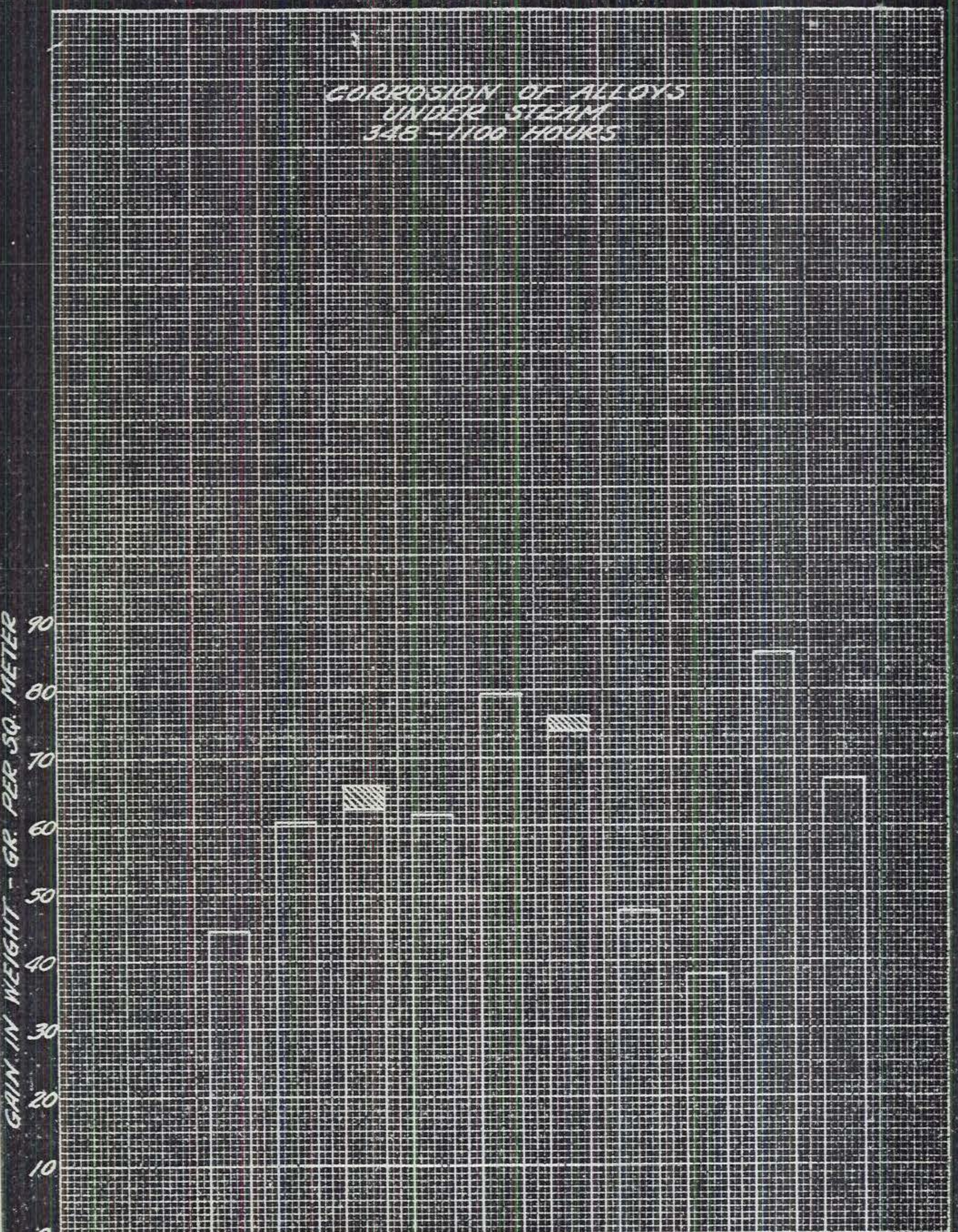


PLATE 22


CORROSION OF ALLOYS
UNDER STEAM
348 - 1100 HOURS
GAIN IN WEIGHT - GR. PER SQ. METER
0
10
20
30
40
50
60
70
80
90
C-MO
BAIN METAL
2
3
4
5
6
7
9
10
ALLOY

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.

DATE

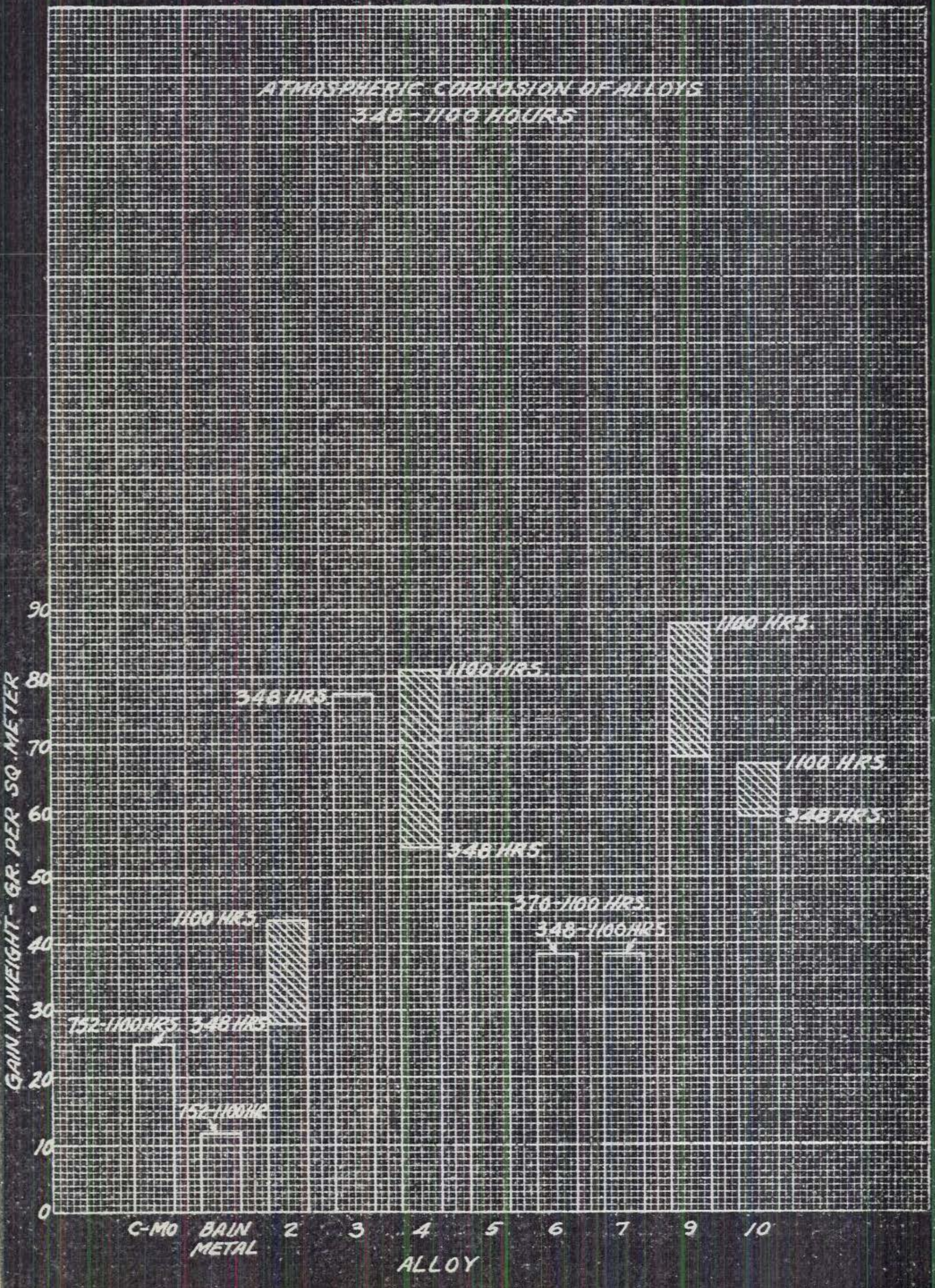
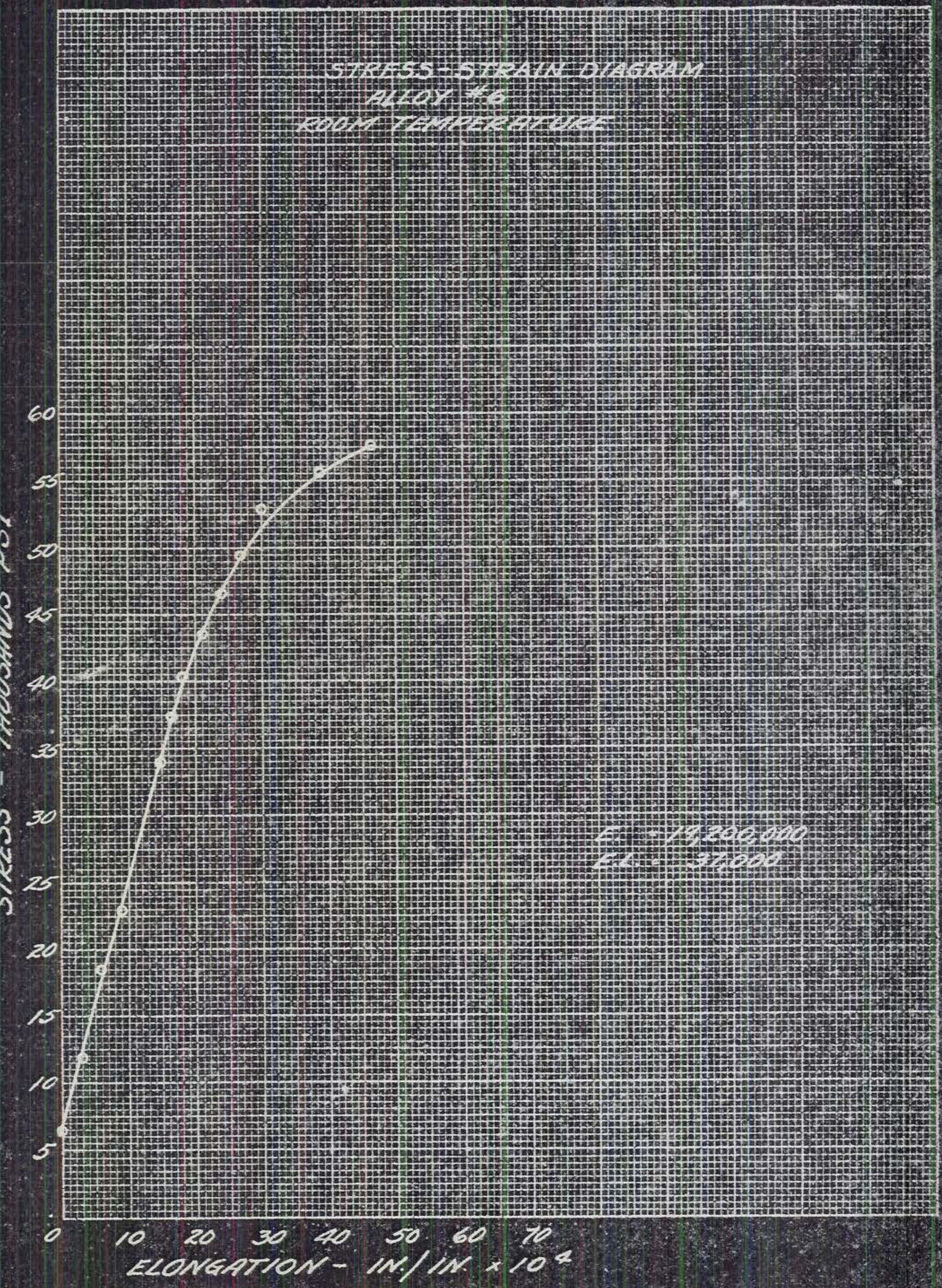


PLATE 24


STRESS-STRAIN DIAGRAM
ALLOY #6
ROOM TEMPERATURE
STRESS - THOUSANDS PSI
60
55
50
45
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
ELONGATION - IN./IN. x 10⁴
E = 19,200,000
E.L. = 37,000

BELLEVUE, D.C.

DATE

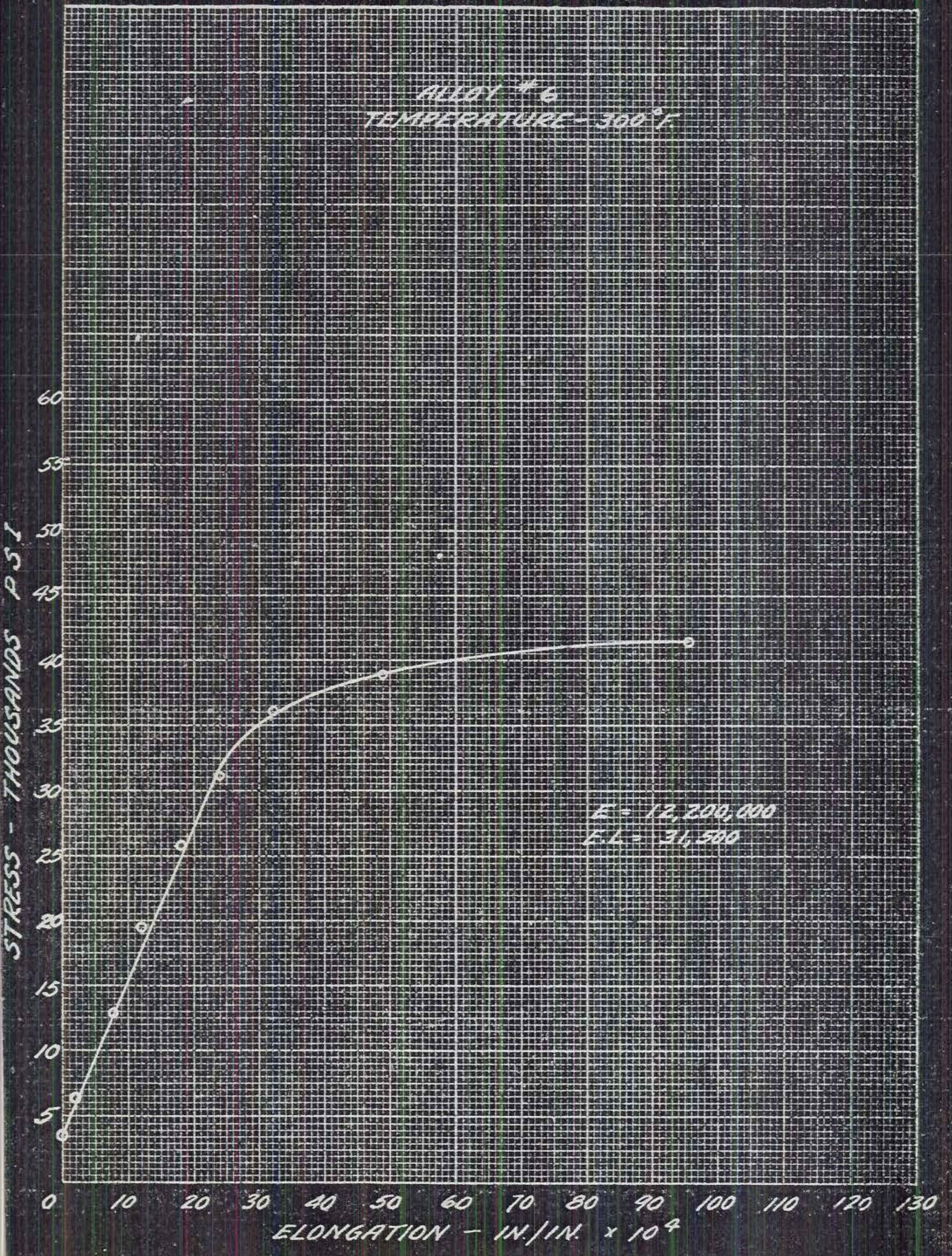


PLATE 26

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DATE

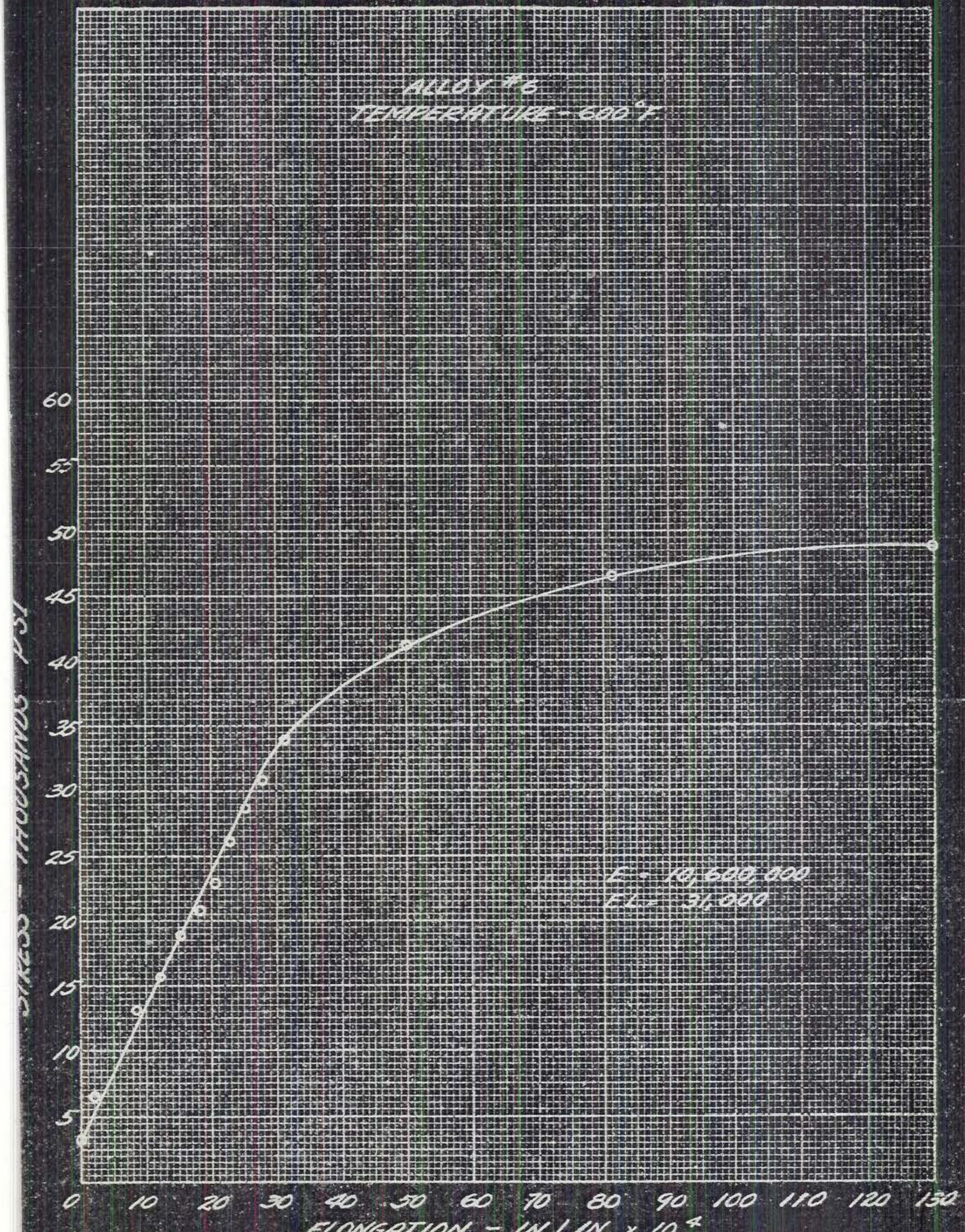


PLATE 27

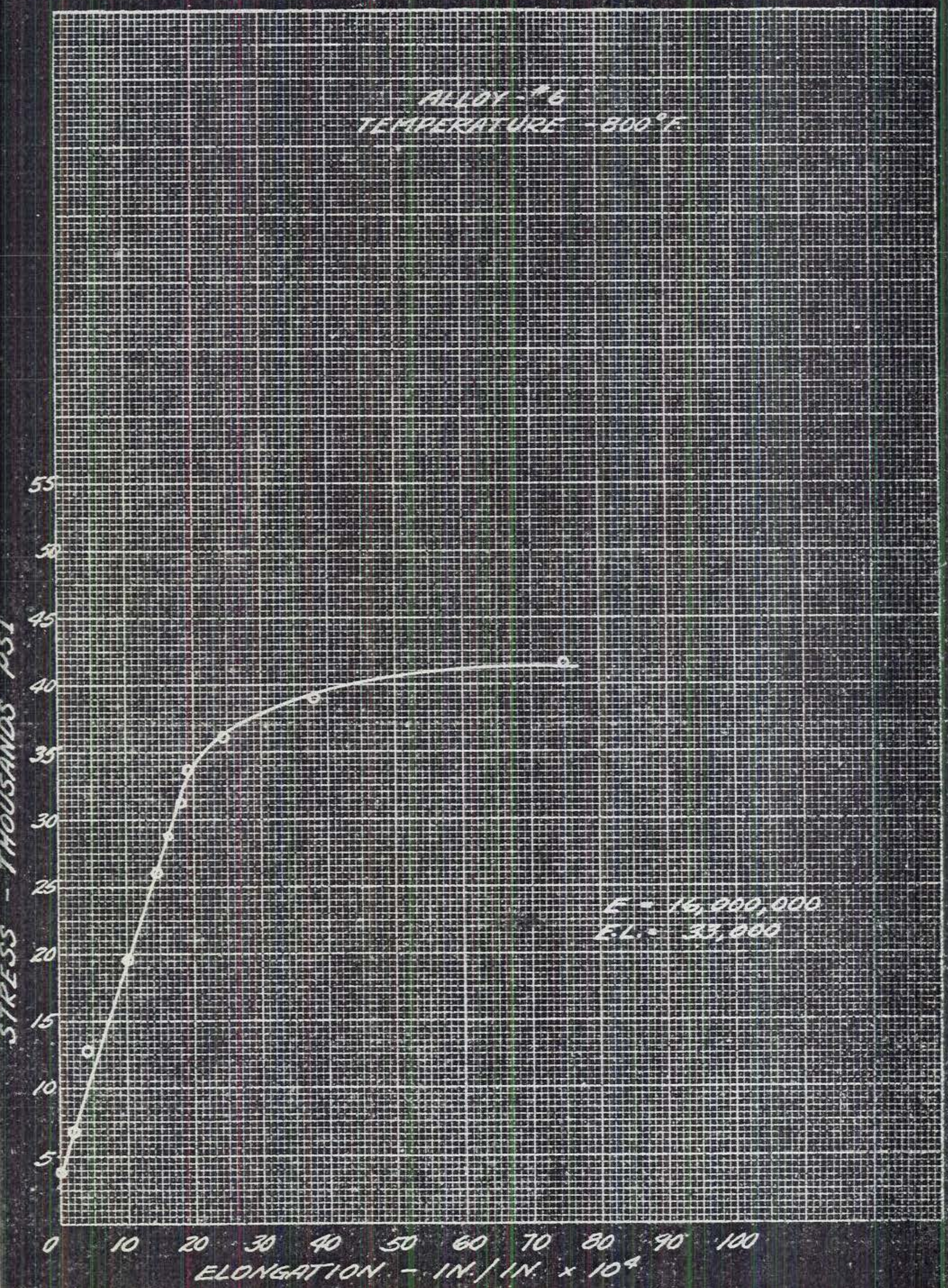

ALLOY - #6
TEMPERATURE - 800°F.
E = 16,000,000
E.L. = 33,000
STRESS - THOUSANDS PSI
5
10
15
20
25
30
35
40
45
50
55
0
10
20
30
40
50
60
70
80
90
100
ELONGATION - IN./IN. x 10⁴

PLATE 28

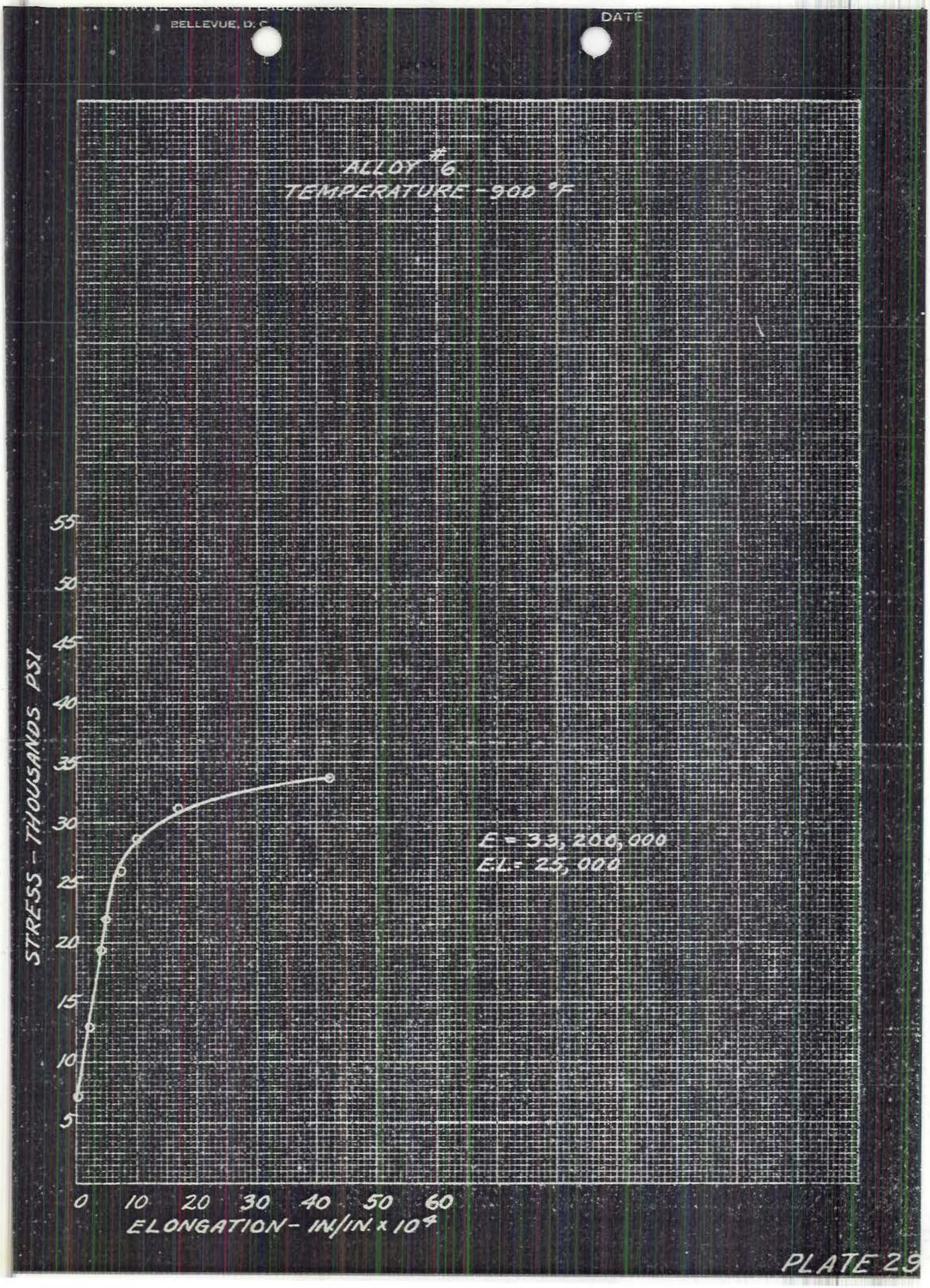

U. S. NAVAL RESEARCH LABORATORY
BELLEVUE, D. C.
DATE
ALLOY #6
TEMPERATURE - 900 °F
E = 33,200,000
E.L. = 25,000
STRESS - THOUSANDS PSI
5
10
15
20
25
30
35
40
45
50
55
0
10
20
30
40
50
60
ELONGATION - IN/IN. x 10⁴

PLATE 29

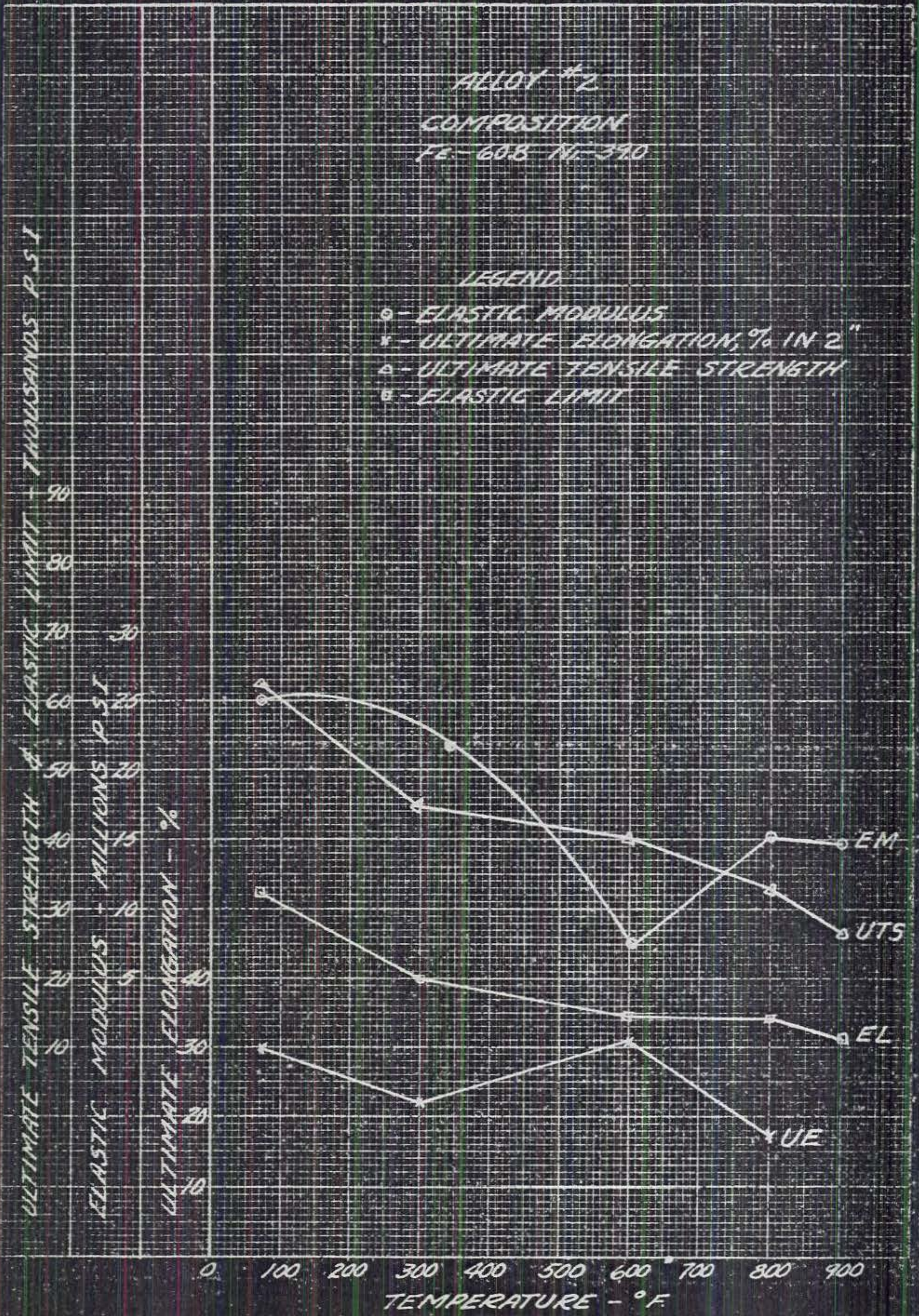
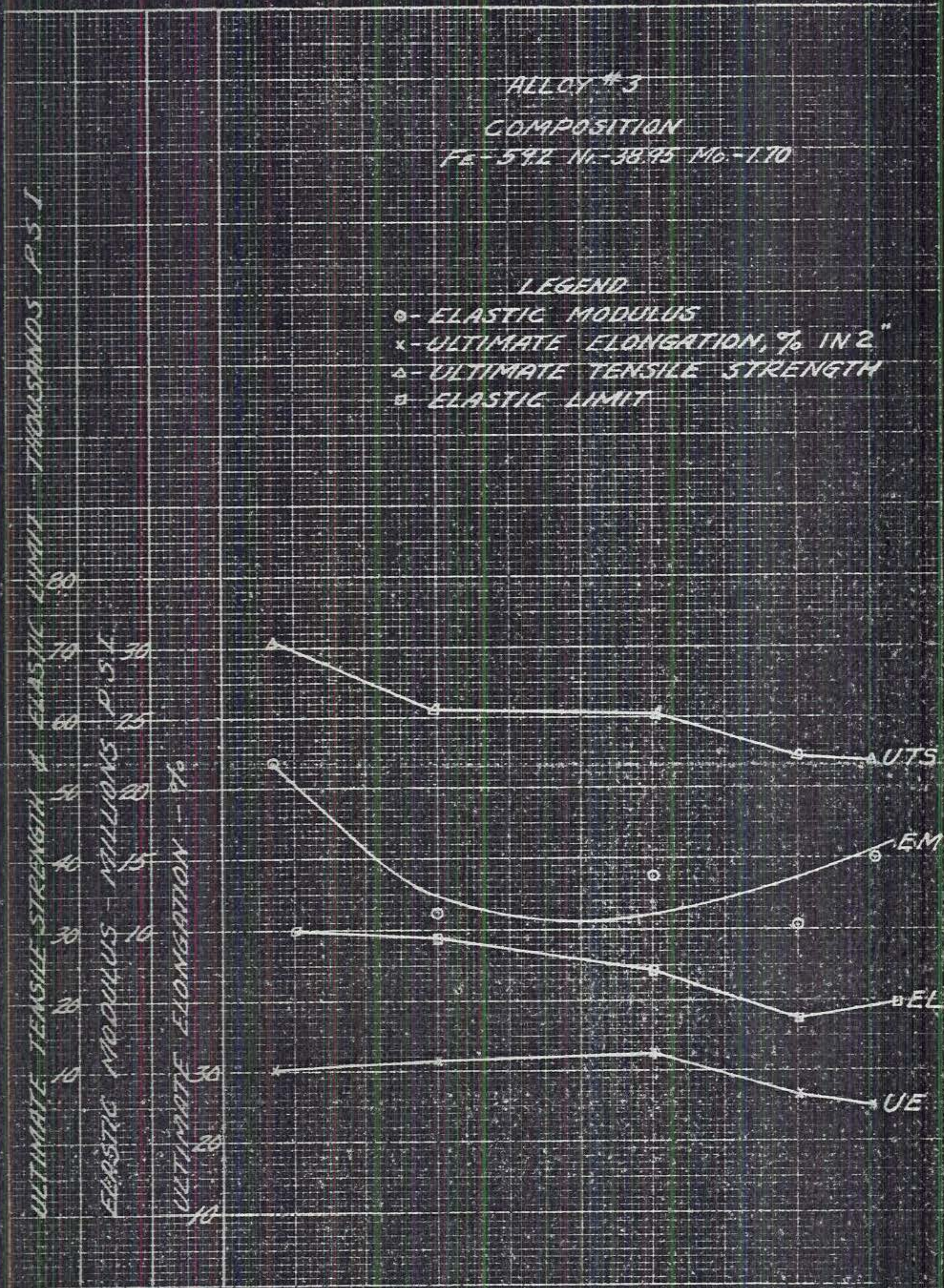

ALLOY #2
COMPOSITION
Fe - 60.8 Ni - 39.0
LEGEND
⊙ - ELASTIC MODULUS
× - ULTIMATE ELONGATION, % IN 2"
△ - ULTIMATE TENSILE STRENGTH
⊡ - ELASTIC LIMIT
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS P.S.I.
ELASTIC MODULUS - MILLIONS P.S.I.
ULTIMATE ELONGATION - %
TEMPERATURE - °F
EM
UTS
EL
UE

PLATE 30


ALLOY #3
COMPOSITION
Fe-59.2 Ni-38.95 Mo-1.70
LEGEND
⊙- ELASTIC MODULUS
×-ULTIMATE ELONGATION, % IN 2"
△-ULTIMATE TENSILE STRENGTH
▫ ELASTIC LIMIT
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS P.S.I.
ELASTIC MODULUS - MILLIONS P.S.I.
ULTIMATE ELONGATION - %
80
70
60
50
40
30
20
10
30
25
20
15
10
30
20
10
0
100
200
300
400
500
600
700
800
900
TEMPERATURE - °F
UTS
EM
EL
UE

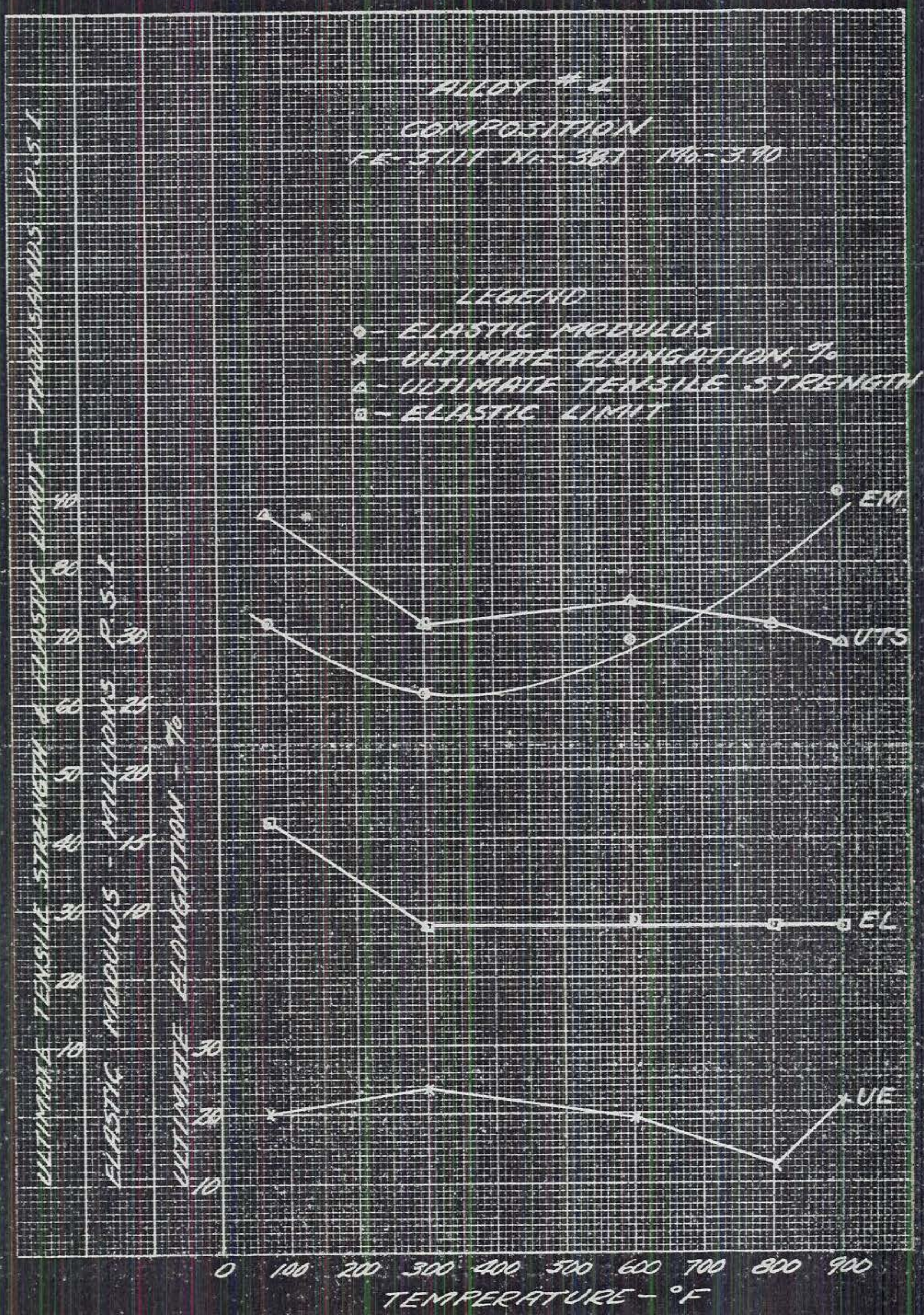

ALLOY # 4
COMPOSITION
FE-51.11 NI-38.1 MO-3.90
LEGEND
⊙ - ELASTIC MODULUS
× - ULTIMATE ELONGATION, %
△ - ULTIMATE TENSILE STRENGTH
⊡ - ELASTIC LIMIT
EM
UTS
EL
UE
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS P.S.I.
ELASTIC MODULUS - MILLIONS P.S.I.
ULTIMATE ELONGATION - %
90
80
70
60
50
40
30
20
10
30
25
20
15
10
30
20
10
0
100
200
300
400
500
600
700
800
900
TEMPERATURE - °F

PLATE 37

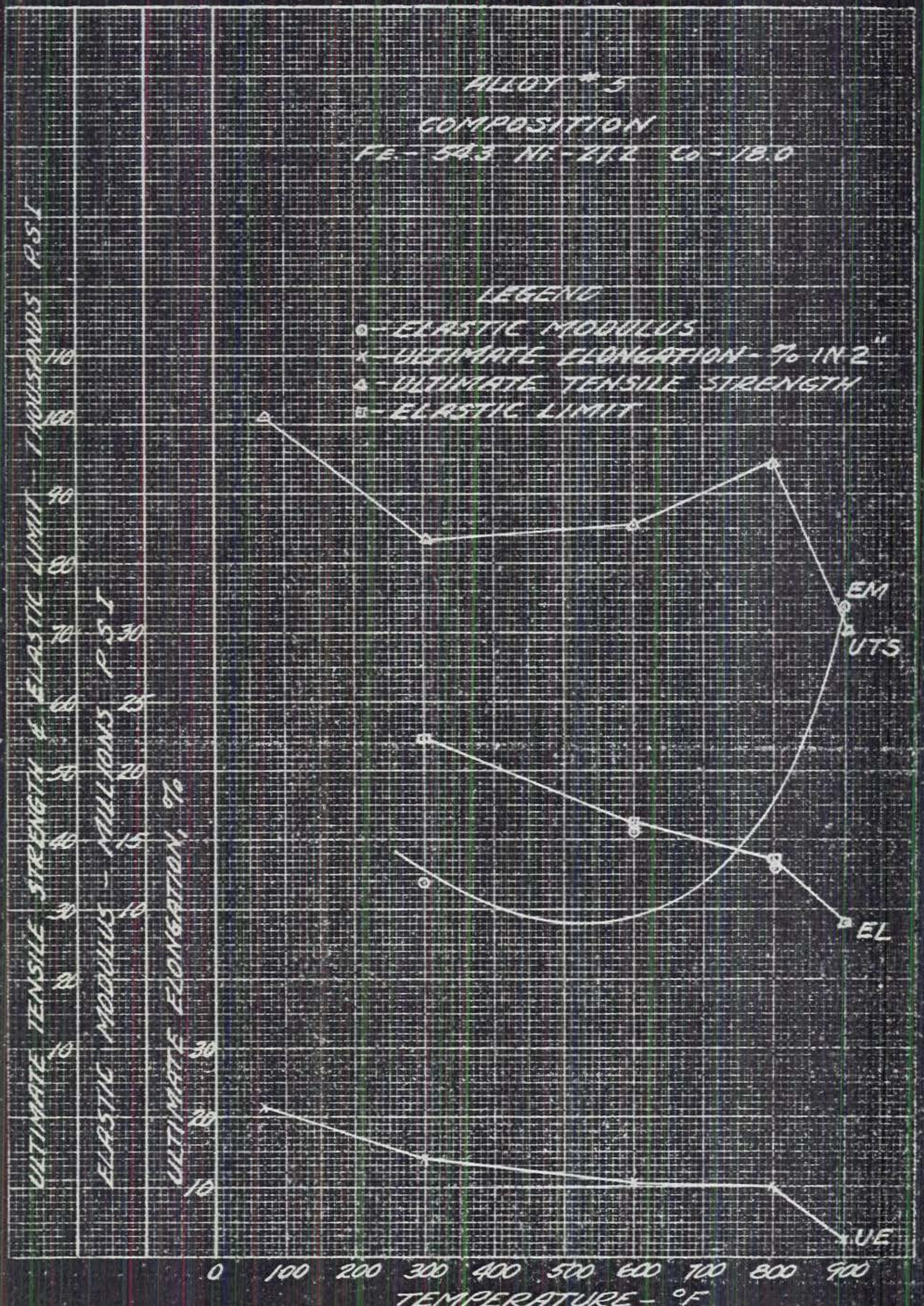

ALLOY #5
COMPOSITION
Fe.-54.3 Ni.-27.2 Co.-18.0
LEGEND
⊙-ELASTIC MODULUS
×-ULTIMATE ELONGATION-% IN 2"
△-ULTIMATE TENSILE STRENGTH
⊡-ELASTIC LIMIT
EM
UTS
EL
UE
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT THOUSANDS PSI
ELASTIC MODULUS - MILLIONS P.S.I
ULTIMATE ELONGATION, %
TEMPERATURE - °F
0 100 200 300 400 500 600 700 800 900

PLATE 33

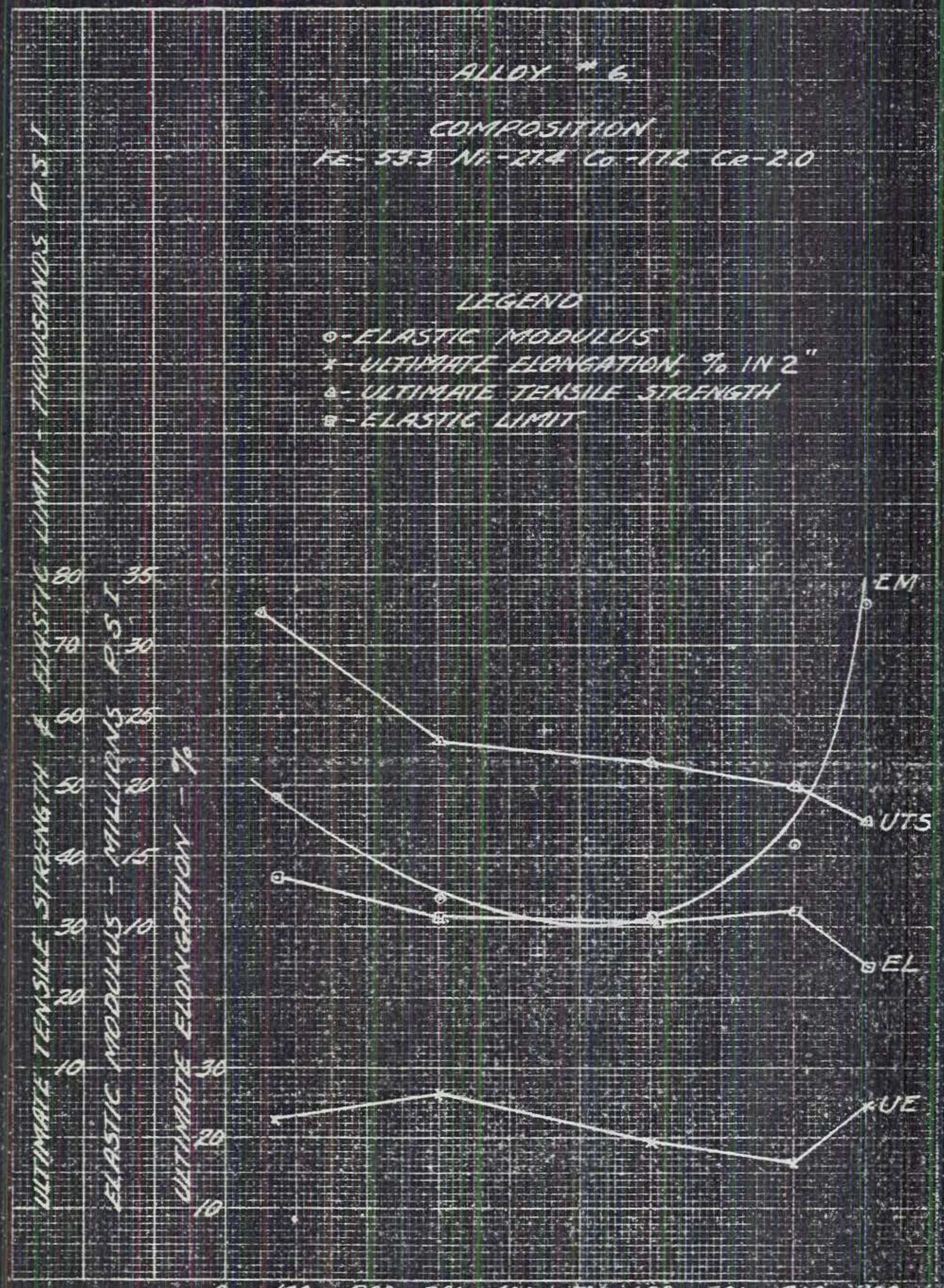

ALLOY # 6
COMPOSITION
Fe-53.3 Ni-27.4 Co-17.2 Cr-2.0
LEGEND
⊙-ELASTIC MODULUS
×-ULTIMATE ELONGATION, % IN 2"
△-ULTIMATE TENSILE STRENGTH
⊡-ELASTIC LIMIT
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS P.S.I.
ELASTIC MODULUS - MILLIONS P.S.I.
ULTIMATE ELONGATION - %
EM
UTS
EL
UE
TEMPERATURE - °F
0 100 200 300 400 500 600 700 800 900

PLATE 34

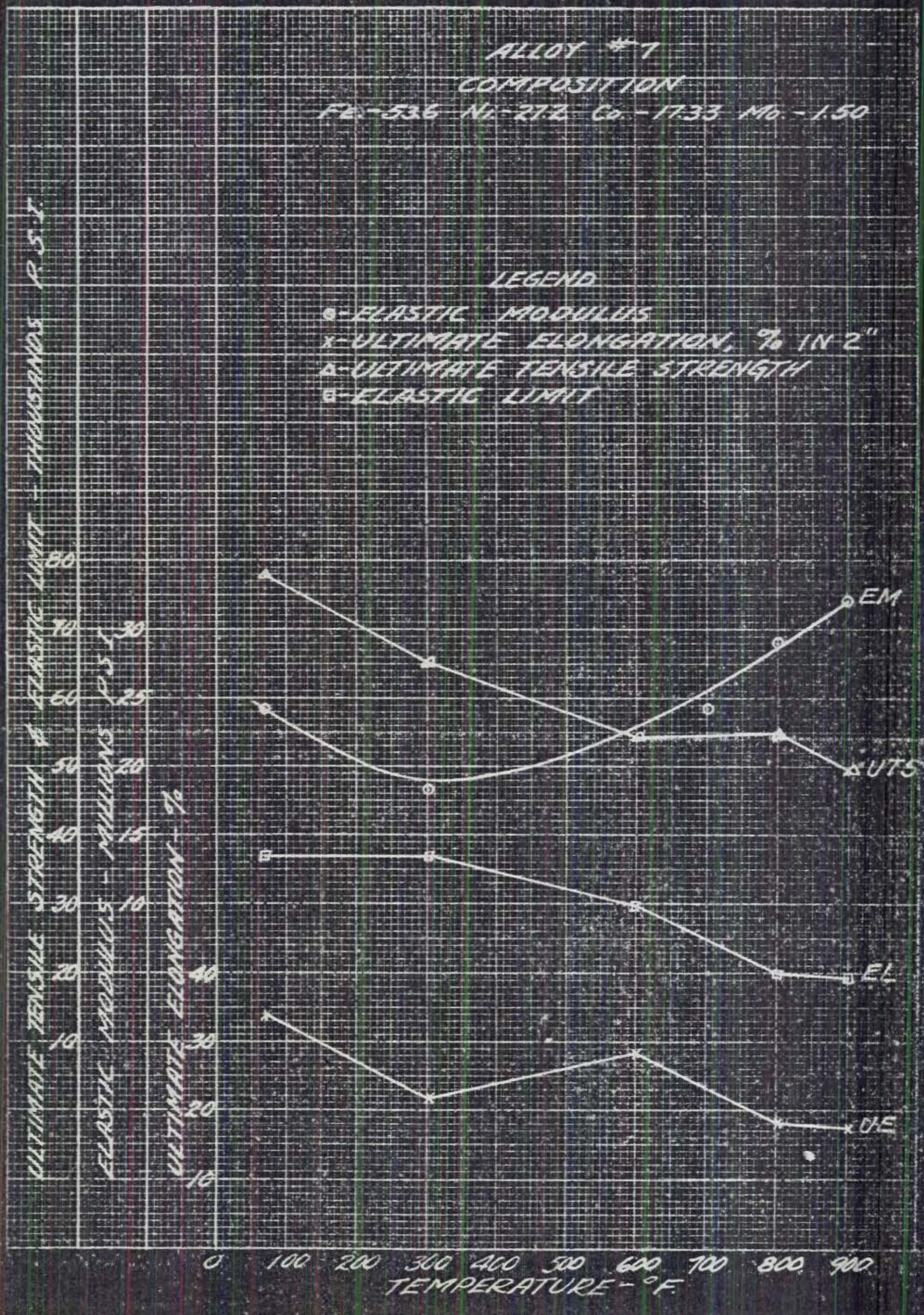
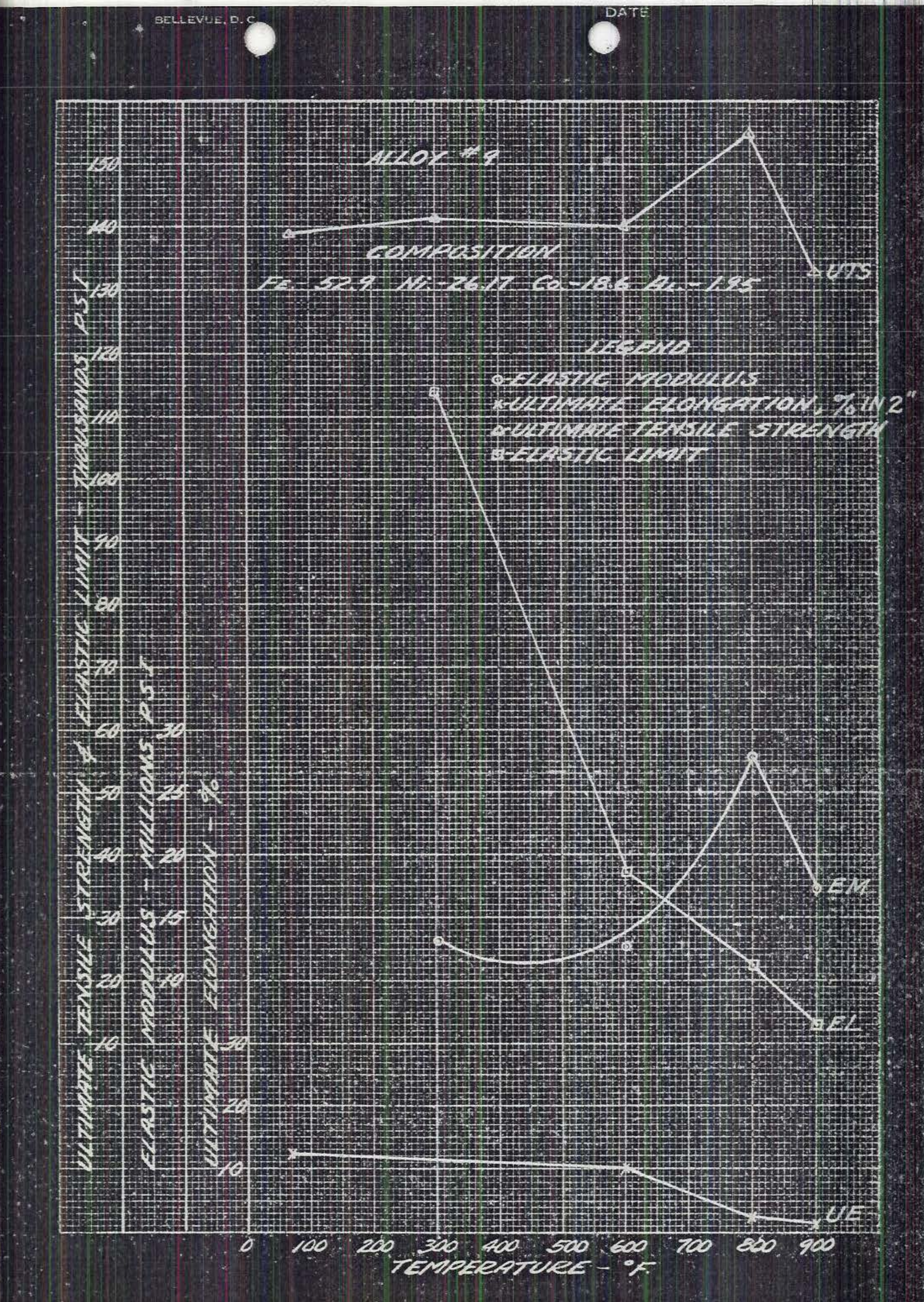
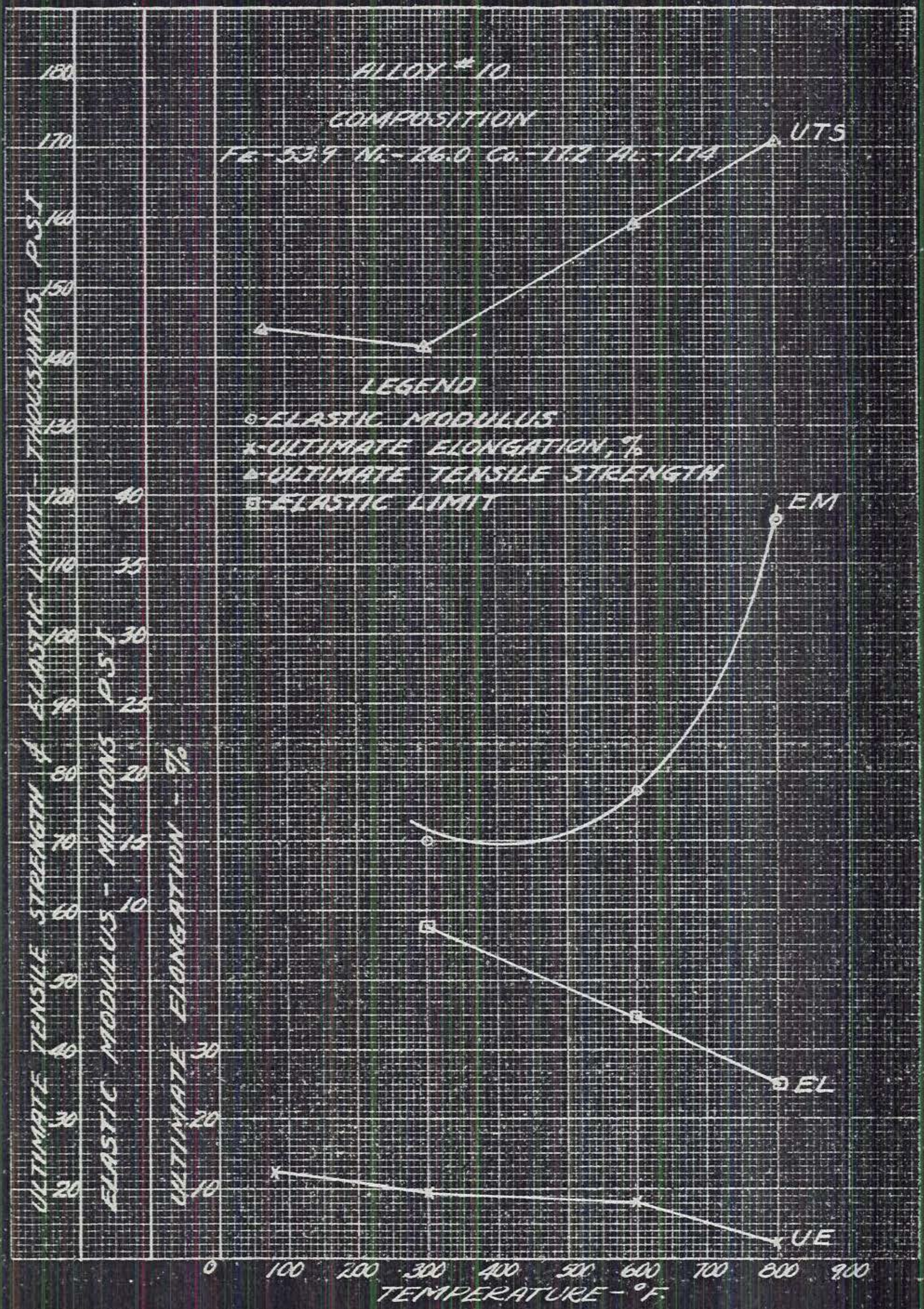

ALLOY #7
COMPOSITION
Fe.-53.6 Ni.-27.2 Co.-17.33 Mo.-1.50
LEGEND
⊙-ELASTIC MODULUS
x-ULTIMATE ELONGATION, % IN 2"
Δ-ULTIMATE TENSILE STRENGTH
⊡-ELASTIC LIMIT
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS P.S.I.
ELASTIC MODULUS - MILLIONS P.S.I.
ULTIMATE ELONGATION - %
80
70
60
50
40
30
20
10
30
25
20
15
10
40
30
20
10
EM
UTS
EL
U.E.
0 100 200 300 400 500 600 700 800 900
TEMPERATURE - °F

PLATE 35


ALLOY #8
COMPOSITION
FE-52.9 NI-26.17 CO-18.6 AL-1.95
LEGEND
○-ELASTIC MODULUS
×-ULTIMATE ELONGATION, % IN 2"
△-ULTIMATE TENSILE STRENGTH
□-ELASTIC LIMIT
UTS
EM
EL
UE
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS P.S.I.
ELASTIC MODULUS - MILLIONS P.S.I.
ULTIMATE ELONGATION - %
TEMPERATURE - °F.
0 100 200 300 400 500 600 700 800 900


ALLOY # 10
COMPOSITION
Fe.-53.9 Ni.-26.0 Co.-17.2 Al.-1.74
LEGEND
⊙-ELASTIC MODULUS
x-ULTIMATE ELONGATION, %
▲-ULTIMATE TENSILE STRENGTH
⊡-ELASTIC LIMIT
UTS
EM
EL
UE
ULTIMATE TENSILE STRENGTH & ELASTIC LIMIT - THOUSANDS PSI
ELASTIC MODULUS - MILLIONS PSI
ULTIMATE ELONGATION - %
TEMPERATURE - °F.
0 100 200 300 400 500 600 700 800 900

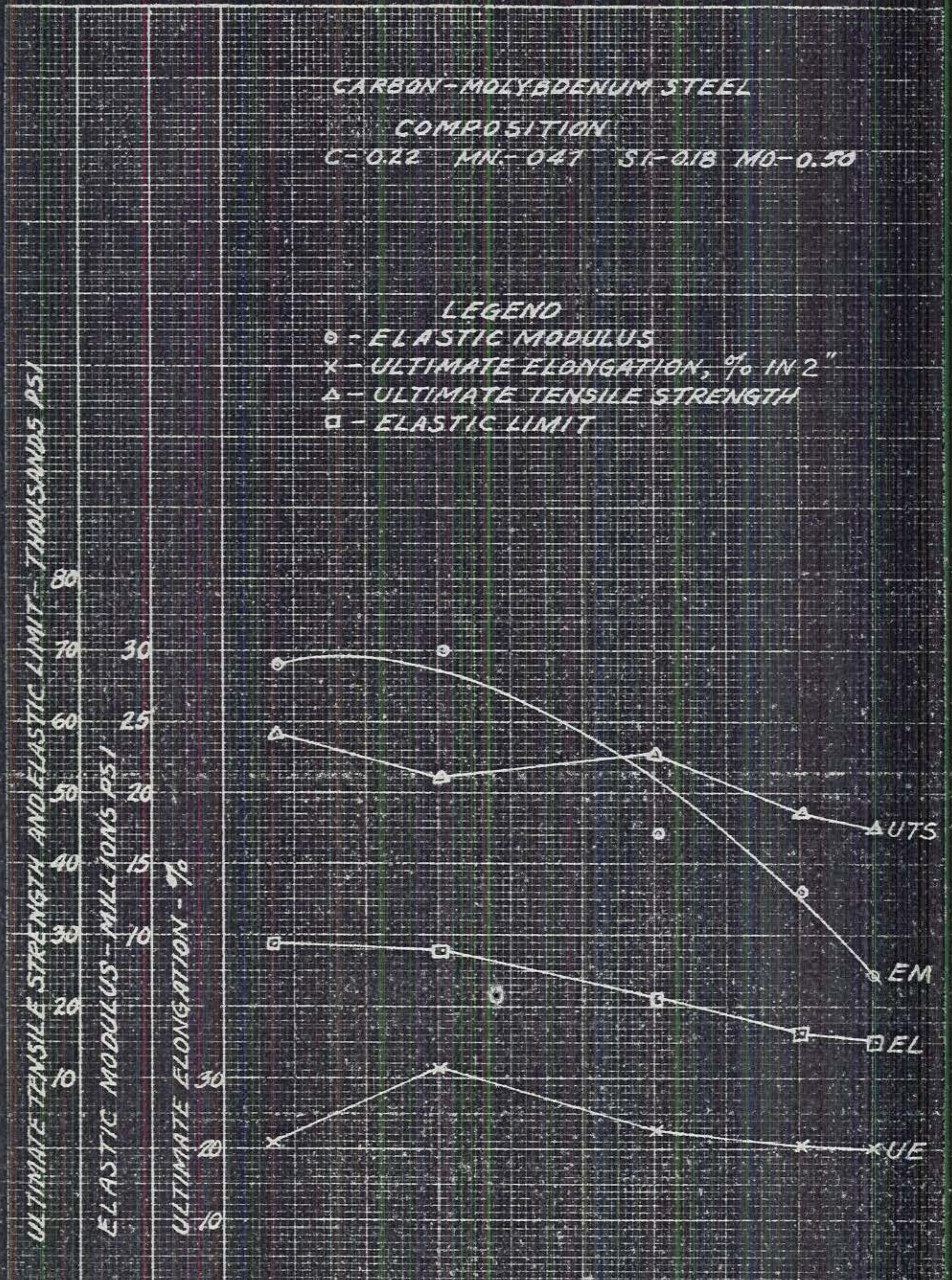

CARBON-MOLYBDENUM STEEL
COMPOSITION
C-0.22 MN.-0.47 SI.-0.18 MO-0.50
LEGEND
⊙ - ELASTIC MODULUS
× - ULTIMATE ELONGATION, % IN 2"
△ - ULTIMATE TENSILE STRENGTH
□ - ELASTIC LIMIT
ULTIMATE TENSILE STRENGTH AND ELASTIC LIMIT - THOUSANDS PSI
ELASTIC MODULUS - MILLIONS PSI
ULTIMATE ELONGATION - %
TEMPERATURE - °F
0 100 200 300 400 500 600 700 800 900
UTS
EM
EL
UE

PLATE 38