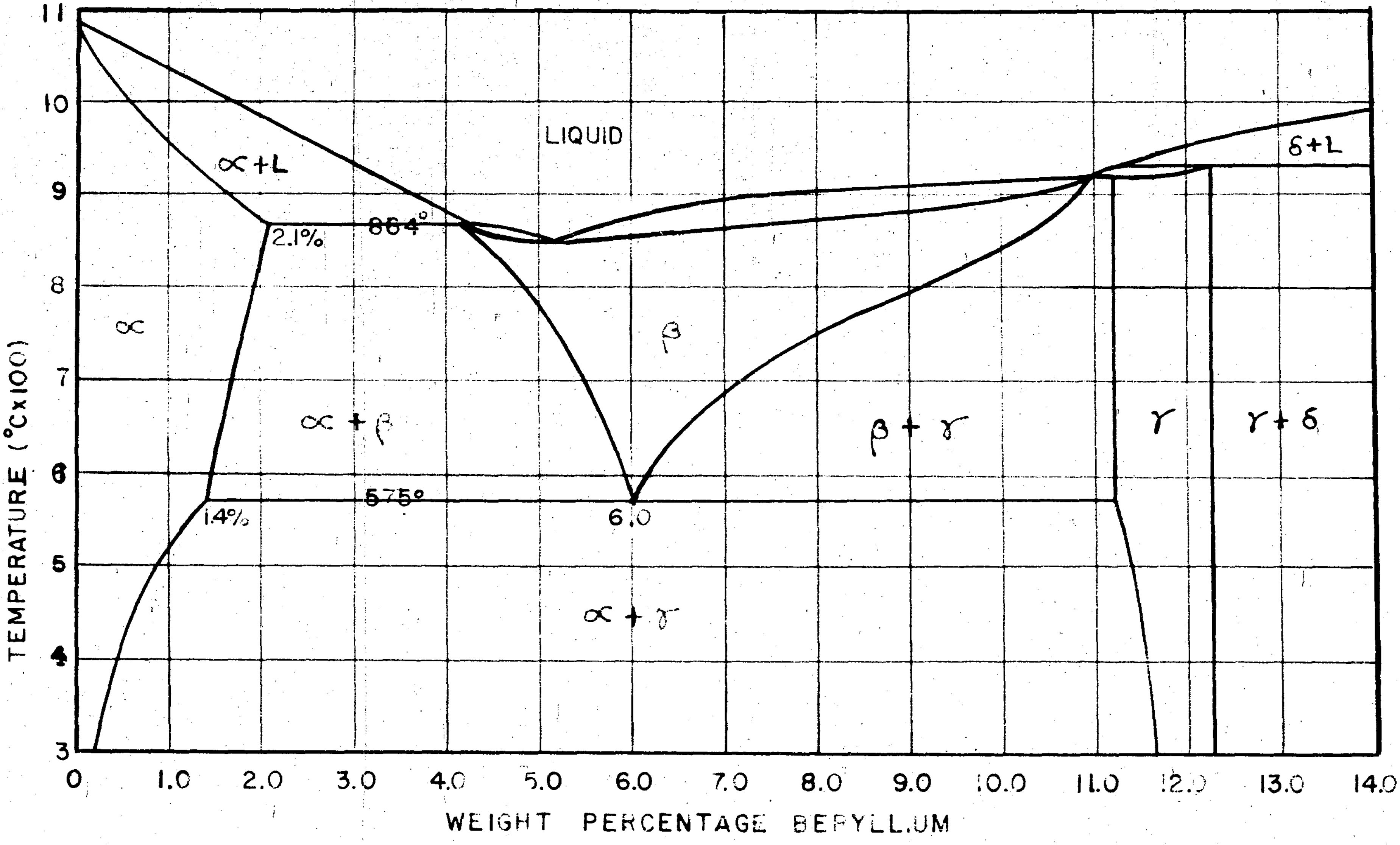

BERYLLIUM—COPPER EQUILIBRIUM DIAGRAM

PHASE DISTRIBUTION AND MICROSTRUCTURAL CHANGES PRODUCED BY ADDING CONTROLLED AMOUNTS OF IRON AND ALUMINUM TO CAST BINARY BERYLLIUM-COPPER ALLOYS

by

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Chemical and Metallurgical Engineering

1949

ACKNOWLEDGEMENT

The author is deeply indebted to Dr. C. C. DeWitt and Mr. D. D. McGrady for their guidance, advice and assistance. Appreciation is also expressed to the other members of the Department of Chemical and Metallurgical Engineering and the Department of Mechanical Engineering who have made helpful suggestions.

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INTRODUCTION

At the time the author became interested in the remarkable properties exhibited by certain beryllium-copper alloys, there were only a few published articles which were concerned with the cast alloys. Such articles that were published were mainly of a non-technical nature or contained such meager information as to be of little practical value. This situation was understandable because most of the uses for the beryllium-copper alloys demanded a wrought product.

It has been found that wrought binary beryllium-copper alloys were not entirely satisfactory because of their relatively coarse-grained structure. The next step in the development of these alloys was to add a material or materials which acted as grain refiners. Both nickel and cobalt were found to perform this service equally well. The alloys thus produced are capable of being heat-treated to produce the optimum property desired.

A previous investigation(1) by the author showed that the maximum hardness and tensile strength obtainable were related to the beryllium content of a cast binary alloy. It appeared that the optimum amount of beryllium should be about 2.25 percent if maximum hardness were desired. If the beryllium content were increased beyond this figure, the maximum hardness remained the same and the tensile strength increased proportionately. Decreasing the beryllium content produced a corresponding decrease in maximum hardness and tensile strength. The observations made regarding the heat-treating cycles may be summarized as follows:

(1) the cast alloys could be solution heat-treated at temperatures up to 1560° F.; the higher the temperature, the shorter the time to produce the equilibrium amount of diffusion of gamma phase into the alpha phase, (2) the maximum hardness, for a particular alloy, obtainable upon aging is dependent upon the time of aging and the temperature of aging; the optimum aging temperature appears to be in the range 600° to 750° F.(1,2) The heat treatment recommended for the cast alloys is, then, in good agreement with the recommended heat-treatment for the wrought alloys.

This investigation was conceived as a result of noting the grain refining propensities of small amounts of cobalt and nickel when added to beryllium-copper alloys. It was felt that if an intentionally added agent has such a marked effect on the grain size, without any other microstructural change, the impurity elements, iron in particular, might be equally potent in the same or larger quantities. Thus, the course of the work was directed toward investigating the phase distribution and microstructural changes produced by adding controlled amounts of iron and aluminum to a cast binary beryllium-copper alloy.

PART I

ALUMINUM ADDITIONS

As was indicated in the introduction, the addition of small amounts of cobalt and/or nickel greatly refines the grain structure of cast beryllium-copper alloys. The wrought alloys then produced are capable of developing the optimum property desired upon proper heat treatment. An inspection of the cobalt-copper and nickel-copper equilibrium systems(4) shows that (1) the cobalt-copper alloy system is of the age-hardening type in the range in which cobalt is added to the beryllium-copper alloys, (2) the nickel-copper alloy system is of the complete solid solubility type. Thus, the action of the two grain refiners must be dependent upon the solubility of the cobalt and nickel in the alpha phase of the beryllium-copper alloys and upon the suppression of the beta phase transformation from the liquid melt. It is difficult to theorize as to the actual mechanism of nucleation but it is believed that the suppression of the beta-phase transformation is the key factor in the nucleation process.

By virtue of the refinement of grain size in the cast and wrought alloys, certain of the physical characteristics of the alloys are greatly enhanced, i.e., tensile strength and elongation are increased with no effect upon the maximum hardness obtainable by proper heat treatment.

An inspection of the copper-aluminum equilibrium diagram (4) shows the aluminum to be completely soluble in the copper in the amounts added. Because of the similarily between nickel and aluminum, when added to copper in small amounts, it may be presumed that their actions would be similar. It was this assumption that led to the collection of the physical property data and photomicrographs as outlined in the procedure.

Table I shows the data obtained on the physical properties of the various heats. The data is shown in graphical form in Figures 2 through 6 . It should be noted that the tensile strength and hardness of the cast alloys increases with increasing aluminum content. The properties developed by the cast alloys are likely to be inconsistent among themselves because of the difficulty in obtaining any degree of homogeneity through casting.

After solution heat-treating the cast alloys, there is evidence of a greater degree of uniformity in the structure. There is very little change in the hardness values but there is an appreciable change in the tensile strength. The tensile strength decreases below the tensile strength of the cast alloys in proportion to the aluminum content. The tensile strength, however, is still greater than that for a cast binary alloy which has been processed in the same manner. The elongation decreases in a proportional manner with increasing tensile strength.

The cast, solution heat-treated and aged alloys show remarkable changes in physical properties. The tensile strength increases with increasing aluminum content up to approximately 1.3% aluminum and then remains fairly constant. The tensile strength in all cases being higher than that obtained by processing a binary alloy in exactly the same manner. It should be noted that full hardening is not obtained when the aluminum content is increased. The elongation is decreased to less than one percent and remains fairly constant.

Typical microstructures are shown in Figures 7 through 30. There are many significant changes in the microstructures and these changes confirm the changes noted in the physical properties. An inspection of the photomicrographs makes it apparent that the aluminum is being distributed in the "beta-phase" in the dendritic interstices. It is equally evident that the aluminum is promoting grain growth instead of acting as a grain refiner as was originally anticipated.

The photomicrographs of the cast and solution heat-treated alloys show no appreciable change in the microstructures. This was to be expected upon the basis of the physical property data.

Probably the most significant change in the microstructure of the cast, solution heat-treated and aged alloys is the disappearance of the gamma phase precipitate at the grain boundaries. It is evident from this disappearing precipitate that the addition of aluminum is "tying up" some of the available beryllium in the "beta-phase".

It is apparent that the addition of aluminum should be avoided because of the adverse effects upon the maximum hardness obtainable on aging and upon the grain size. There is a beneficial effect, however, in that the hardness and tensile strengths of the cast alloys may be increased approximately fifteen percent over the cast binary alloys.

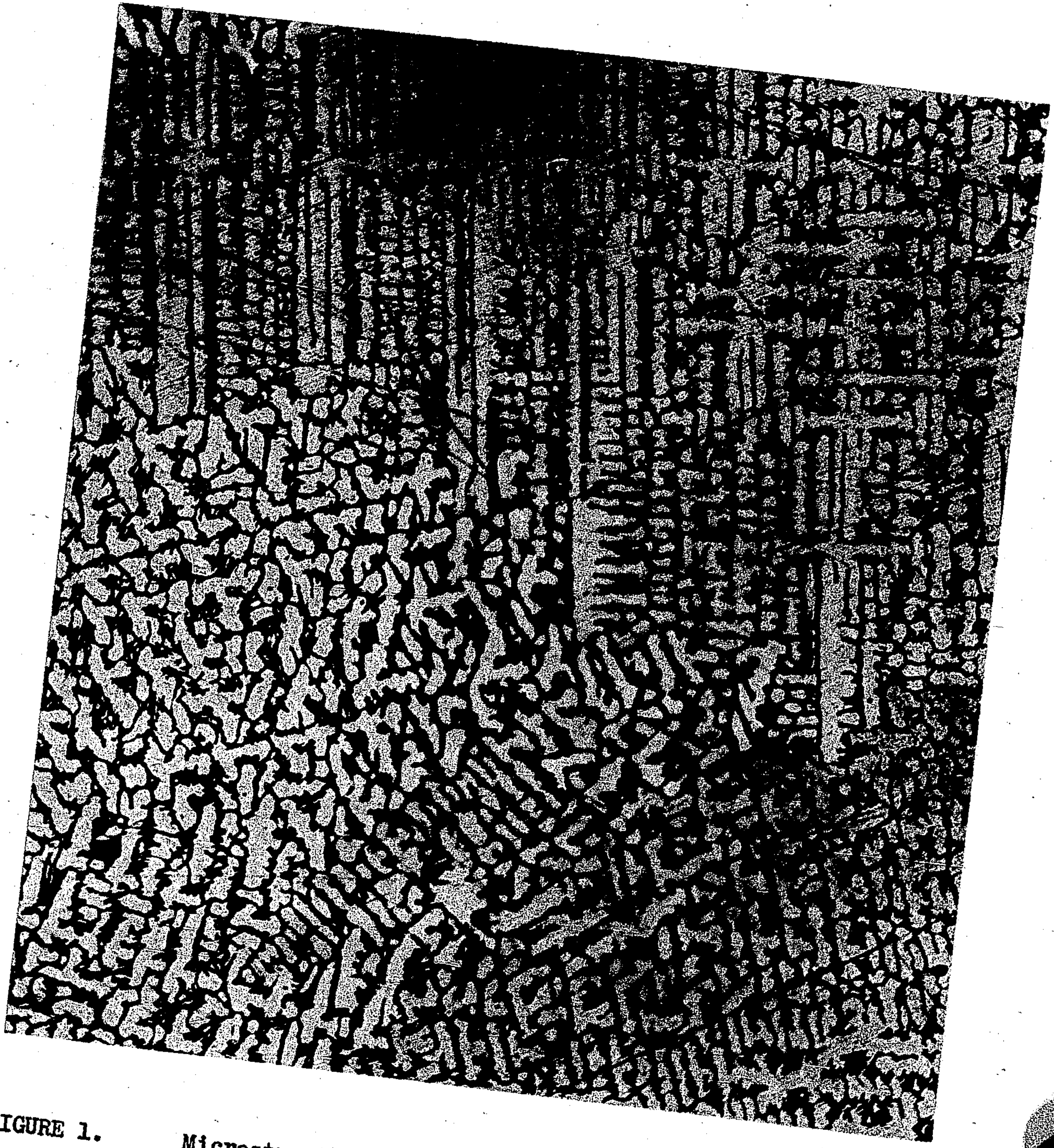

FIGURE 1. Microstructure of a cast alloy containing 2.26% Be- 2.09% Al- 95.60% Cu.

Etch: Ferric Chloride

Magnification: 100X

TABLE I — PHYSICAL PROPERTIES of Be-Cu-Al ALLOYS

	AS CAST			CAST, SOLUTION HEAT-TREATED 72 hrs. at 1525° F			CAST, SOLN. HEAT-TREATED and AGED 2.5hrs at 700° F		
Percent Aluminum in Alloy	Ultimate Tensile Strength	Elongation in 2 inches	Rockwell B Hardness	Ultimate Tensile Strength	Elongation in 2 inches	Rockwell B Hardness	Ultimate Tensile Strength	Elongation in 2 inches	Rockwell C Hardness
0.03%	55,000 p.s.i.	17.8%	76	50,800 p.s.i.	16.3%	74	111,000 p.s.i.	0.65%	41
0.31%	53,400 p.s.i.	#	78	55,500 p.s.i.	13.2%	78	112,900 p.s.i.	0.70%	41
0.60%	59,100 p.s.i.	13.3%	76	53,300 p.s.i.	11.0%	81	113,900 p.s.i.	0.75%	40
0.84%	61,200 p.s.i.	11.6%	82	57,300 p.s.i.	8.9%	83	120,500 p.s.i.	0.75%	40
1.07%	69,900 p.s.i.	13.1%	87	61,600 p.s.i.	#	87	125,200 p.s.i.	0.80%	39
1.52%	82,200 p.s.i.	#	90	67,800 p.s.i.	8.0%	87	126,600 p.s.i.	0.85%	39
2.09%	90,000 p.s.i.	19.1%	96	74,100 p.s.i.	7.1%	98	126,100 p.s.i.	0.85%	38

Broke Outside Gauge Marks.

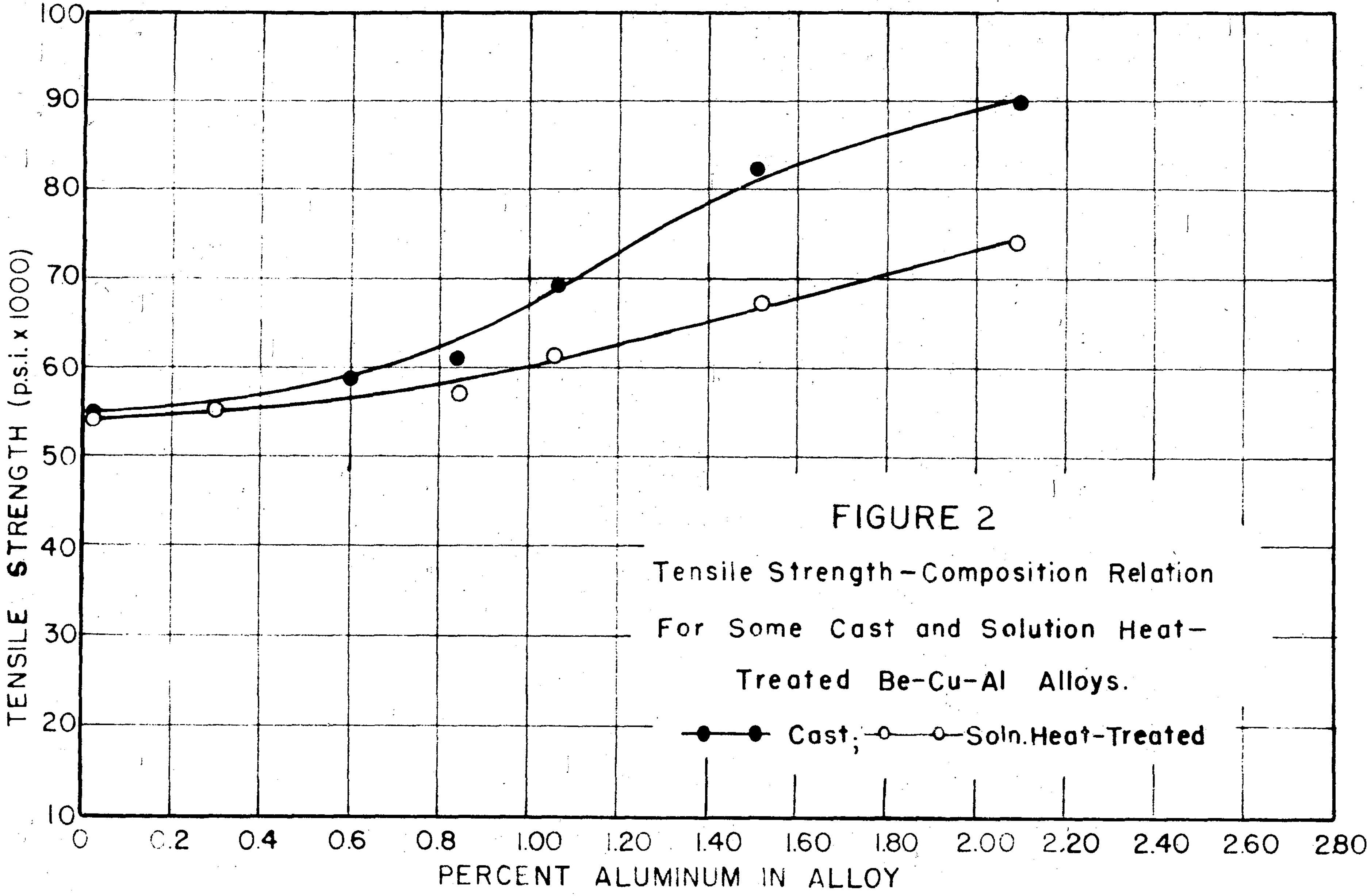

FIGURE 2

Tensile Strength – Composition Relation For Some Cast and Solution Heat-Treated Be-Cu-Al Alloys.

●—● Cast; ○—○ Soln. Heat-Treated

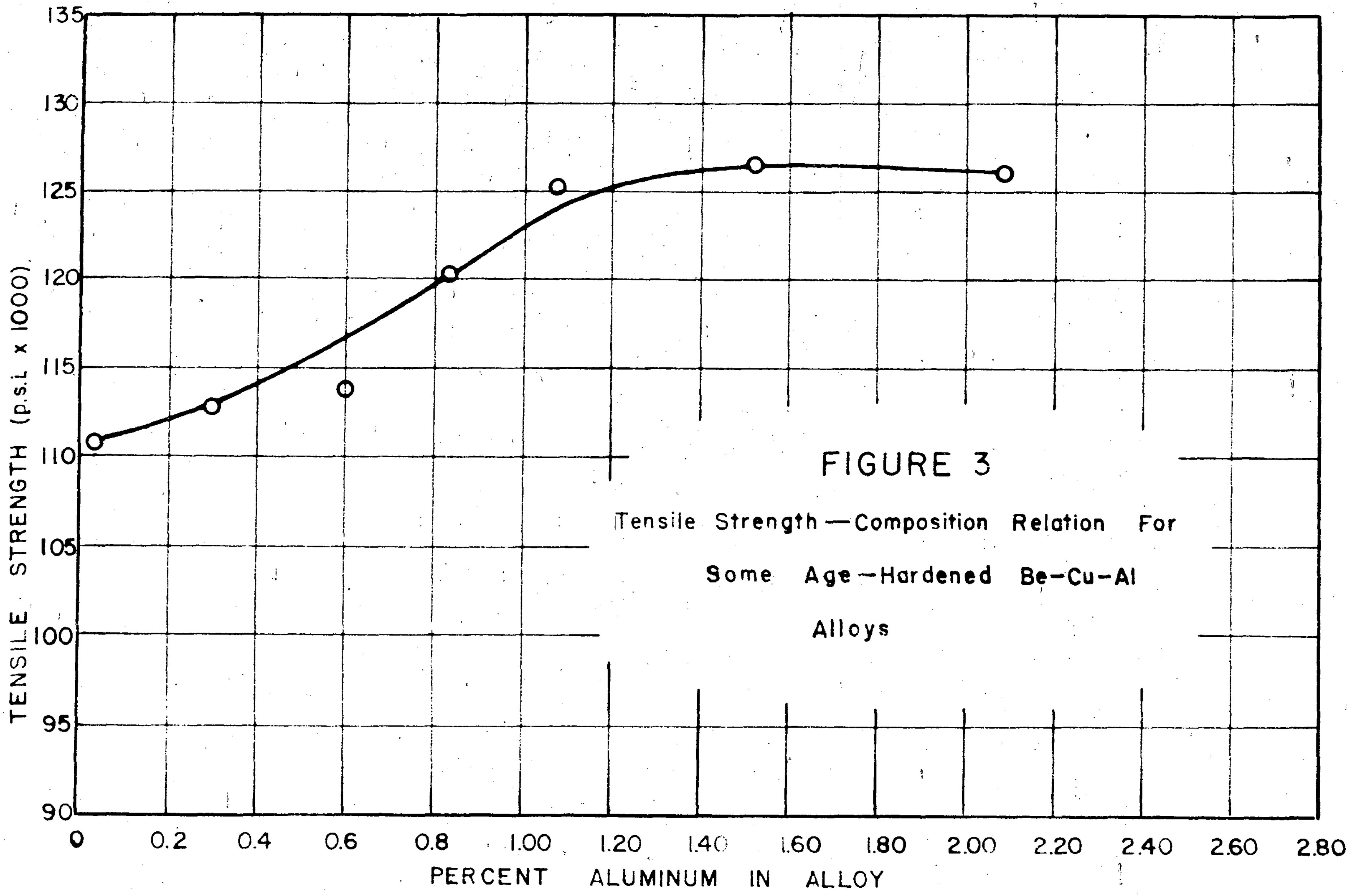

FIGURE 3

Tensile Strength — Composition Relation For Some Age-Hardened Be-Cu-Al Alloys

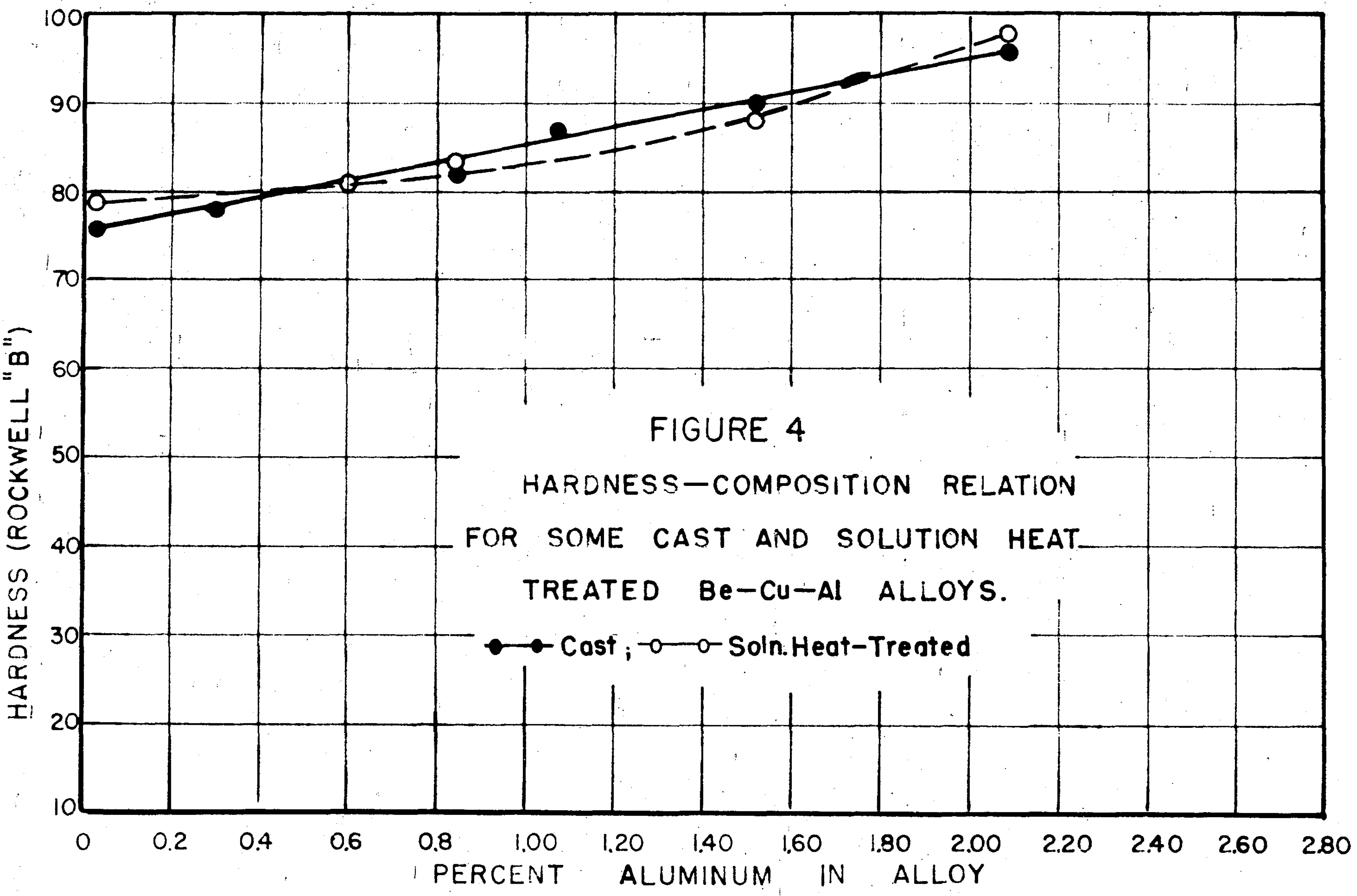

FIGURE 4

HARDNESS—COMPOSITION RELATION FOR SOME CAST AND SOLUTION HEAT TREATED Be—Cu—Al ALLOYS.

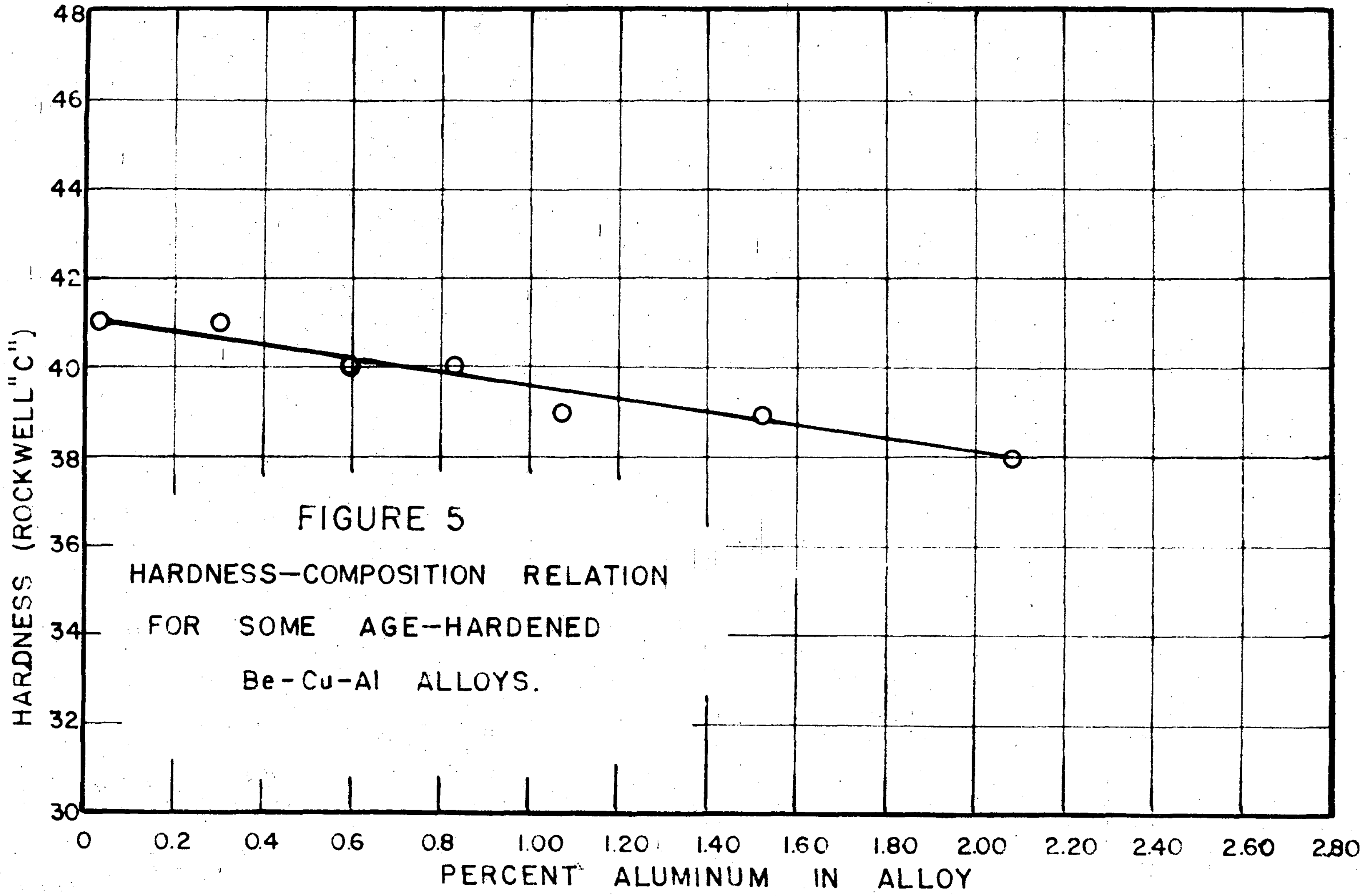

FIGURE 5

HARDNESS—COMPOSITION RELATION FOR SOME AGE-HARDENED Be-Cu-Al ALLOYS.

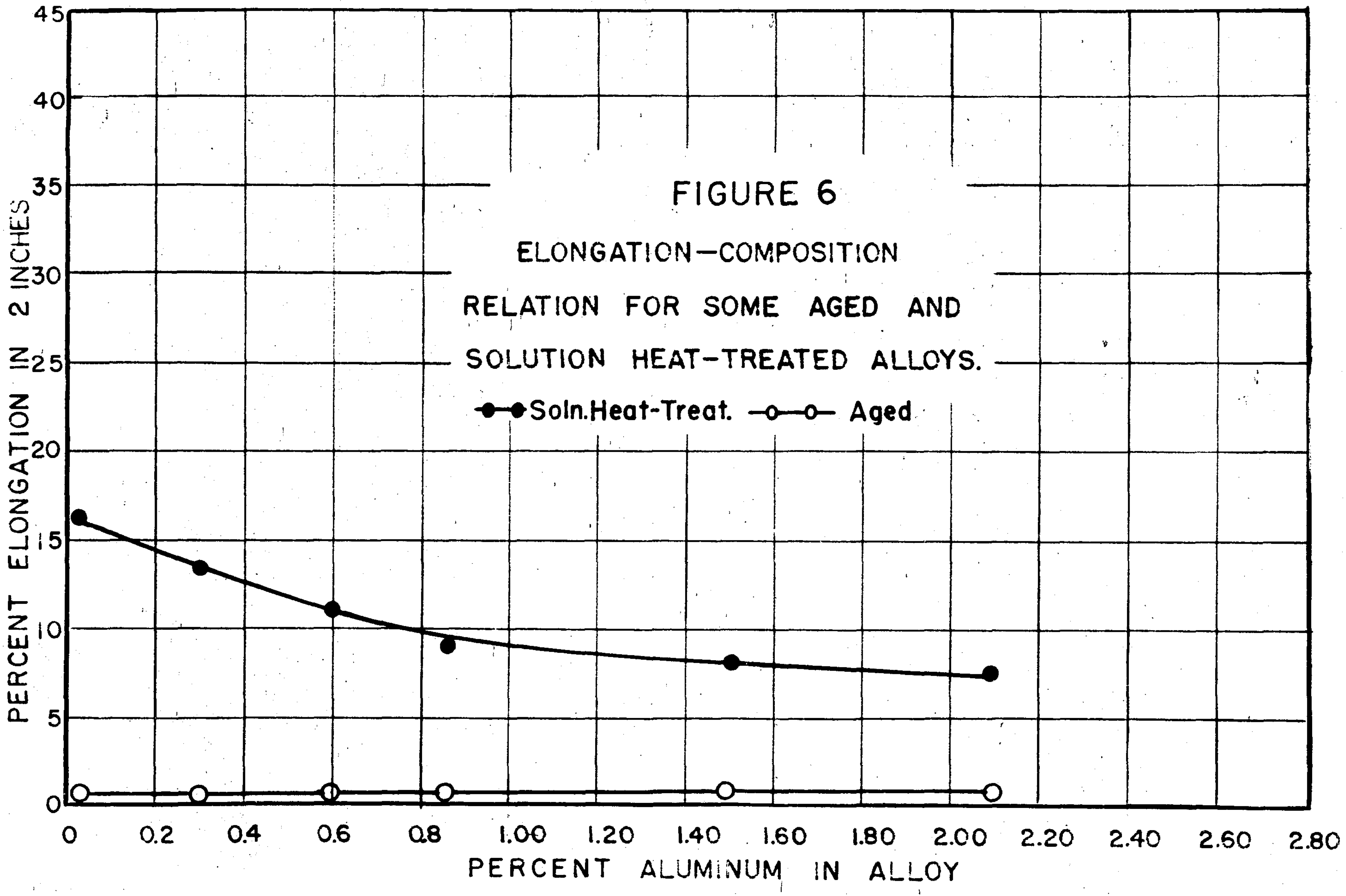

FIGURE 6

ELONGATION—COMPOSITION RELATION FOR SOME AGED AND SOLUTION HEAT-TREATED ALLOYS.

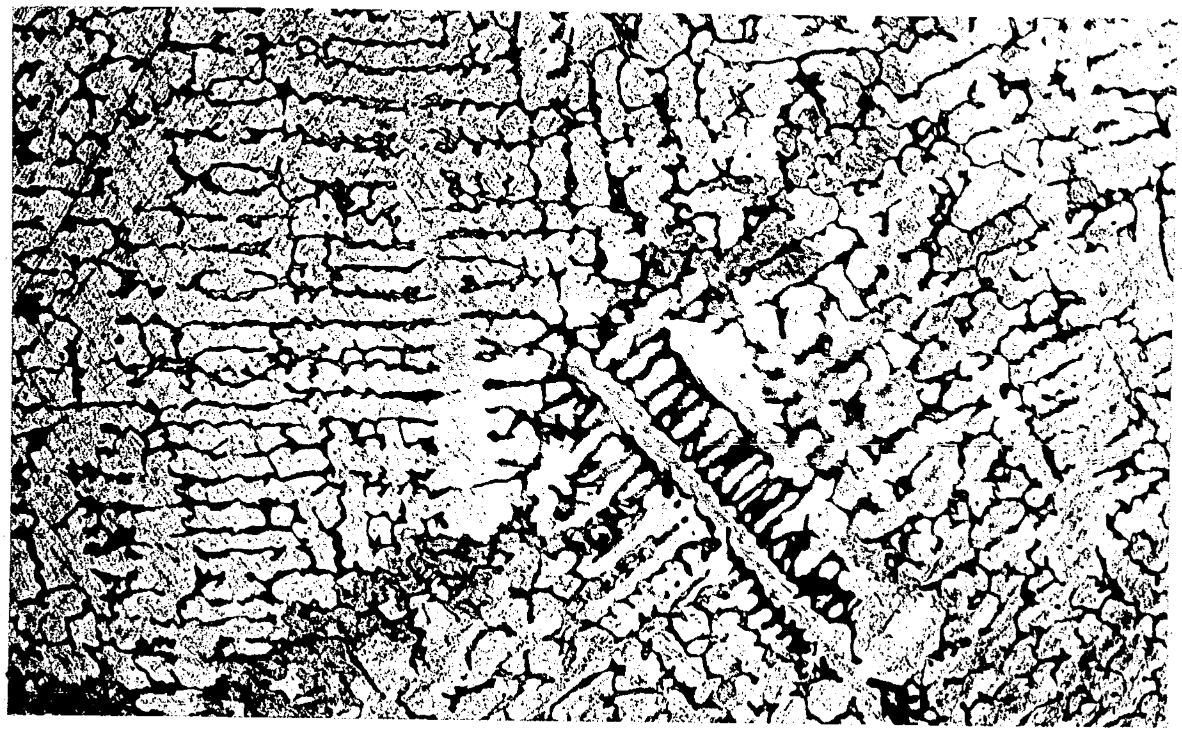

FIGURE 7. Microstructure of a cast alloy containing 2.25% Be-0.03% Al- 97.63% Cu.
Etch: Ferric Chloride Magnification: 100X

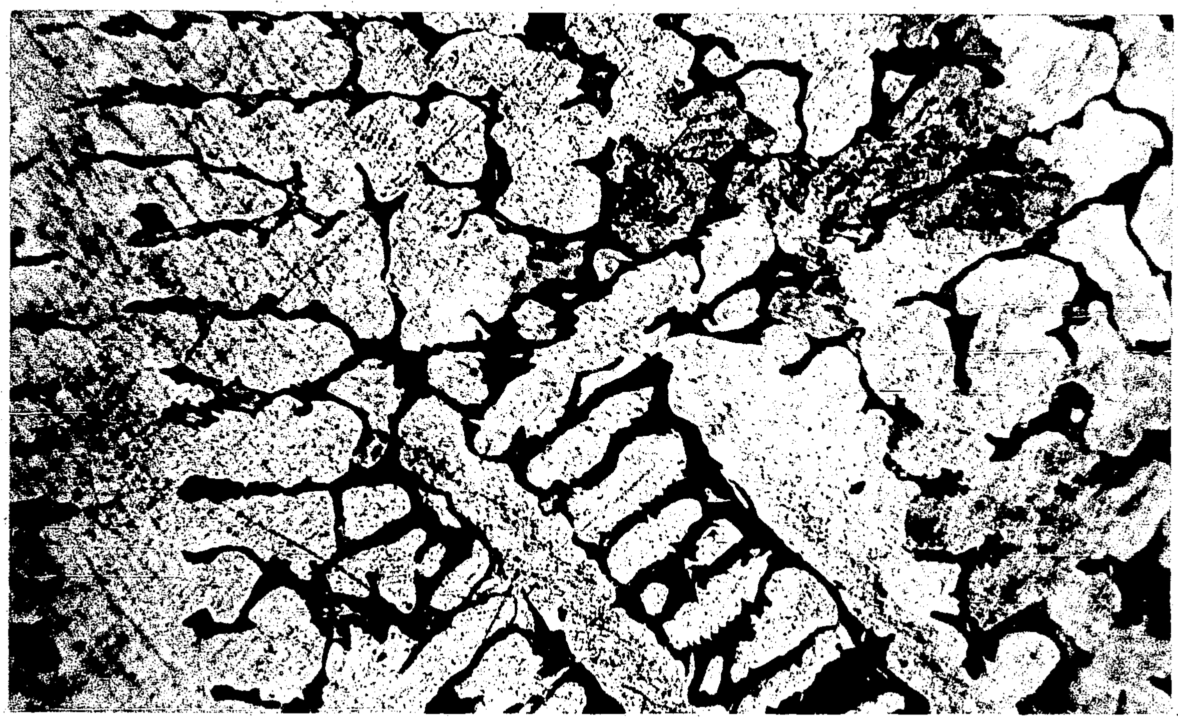

FIGURE 8. Same spot as FIGURE 7. Magnification: 250X

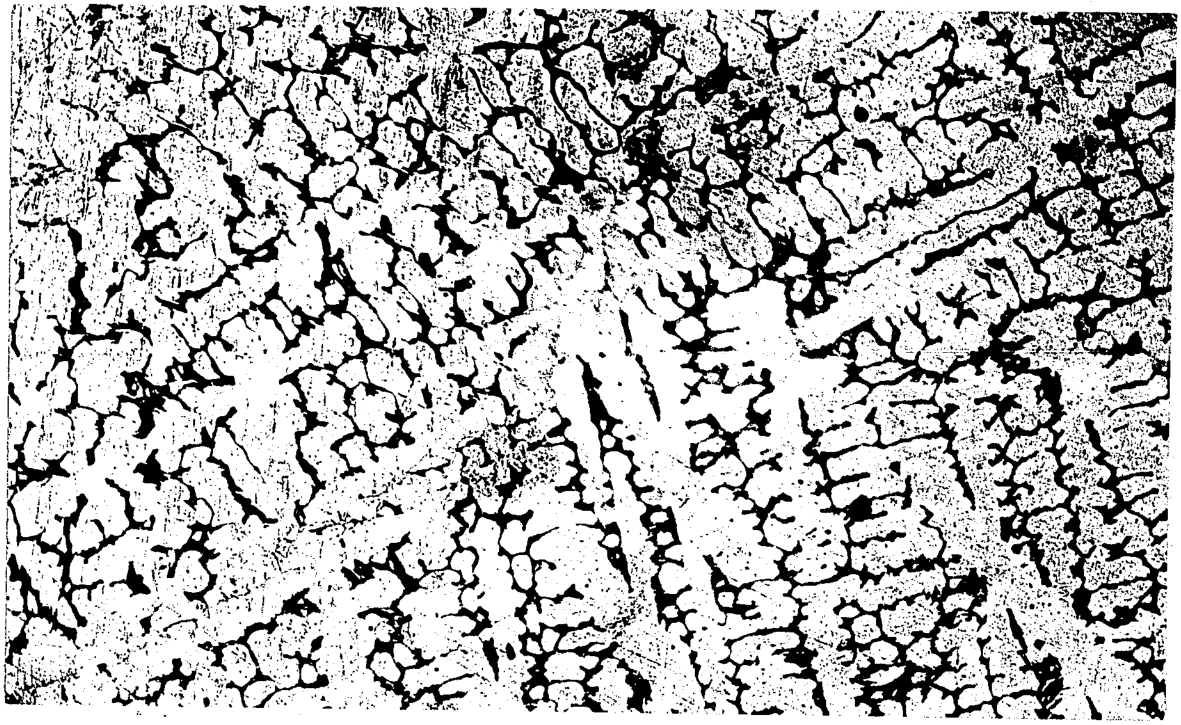

FIGURE 9. Microstructure of a cast alloy containing 2.26% Be-0.60% Al- 97.12% Cu.
Etch: Ferric Chloride Magnification: 100X

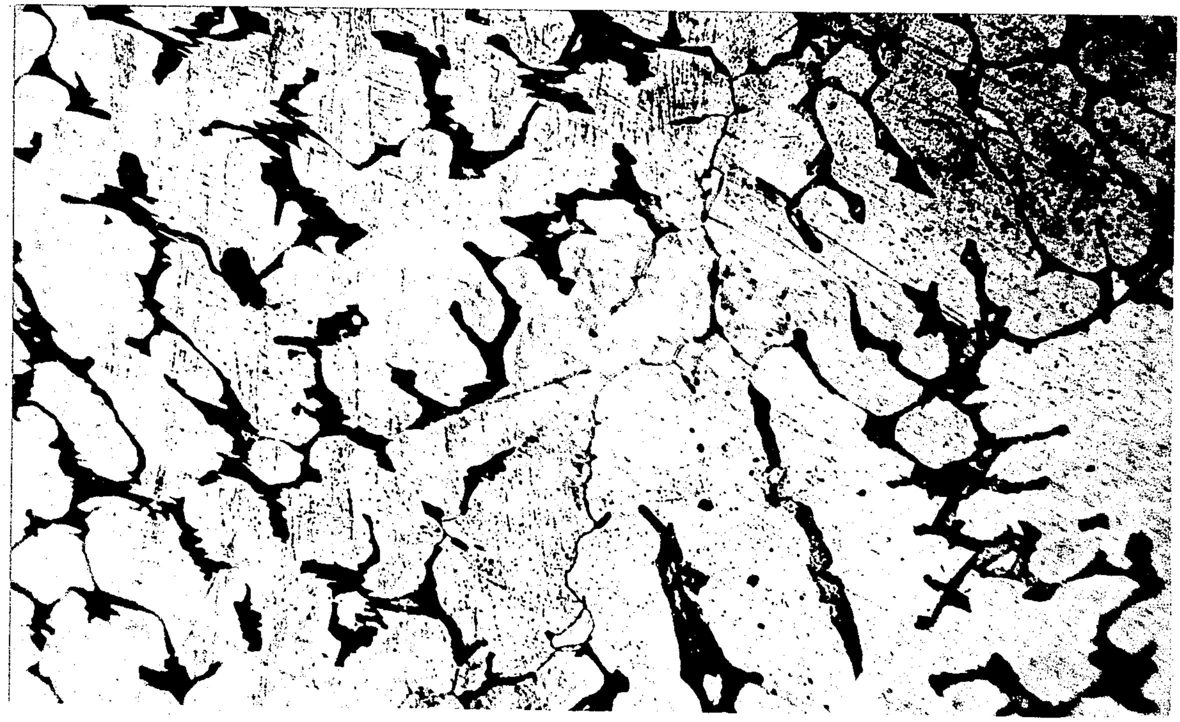

FIGURE 10. Same spot as FIGURE 9. Magnification: 250X

FIGURE 11. Microstructure of a cast alloy containing 2.18% Be-1.07% Al- 96.69% Cu.

Etch: Ferric Chloride Magnification: 100X

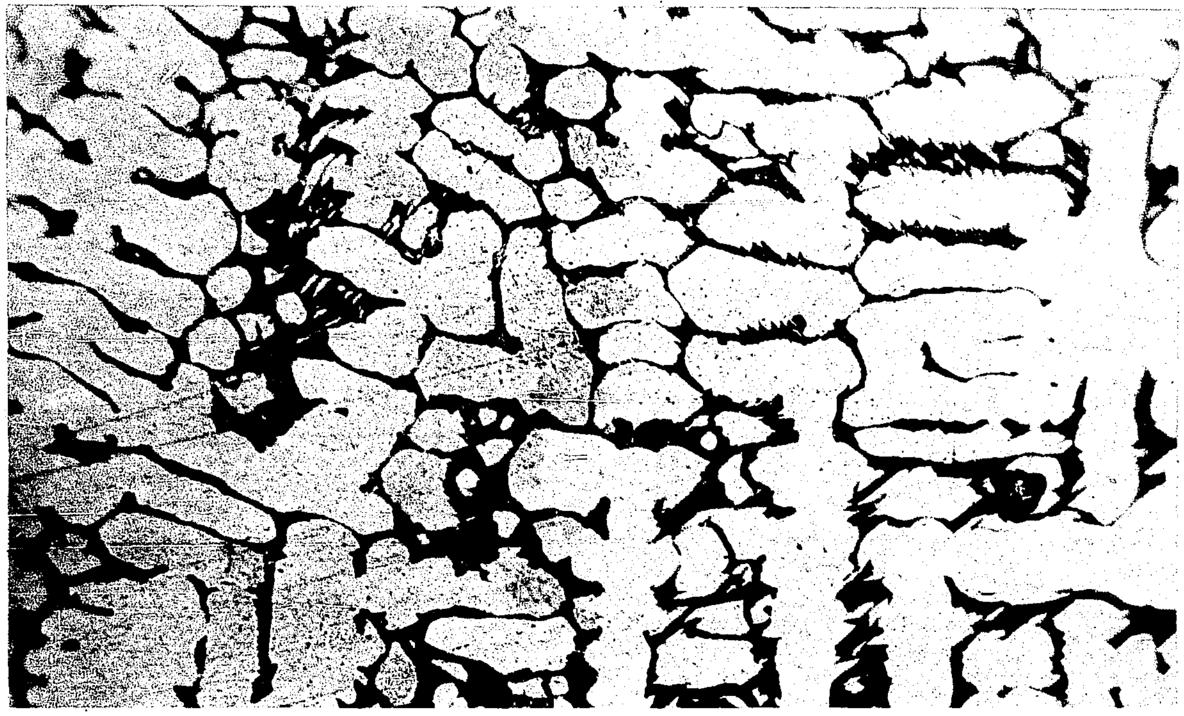

FIGURE 12. Same spot as FIGURE 11. Magnification: 250X

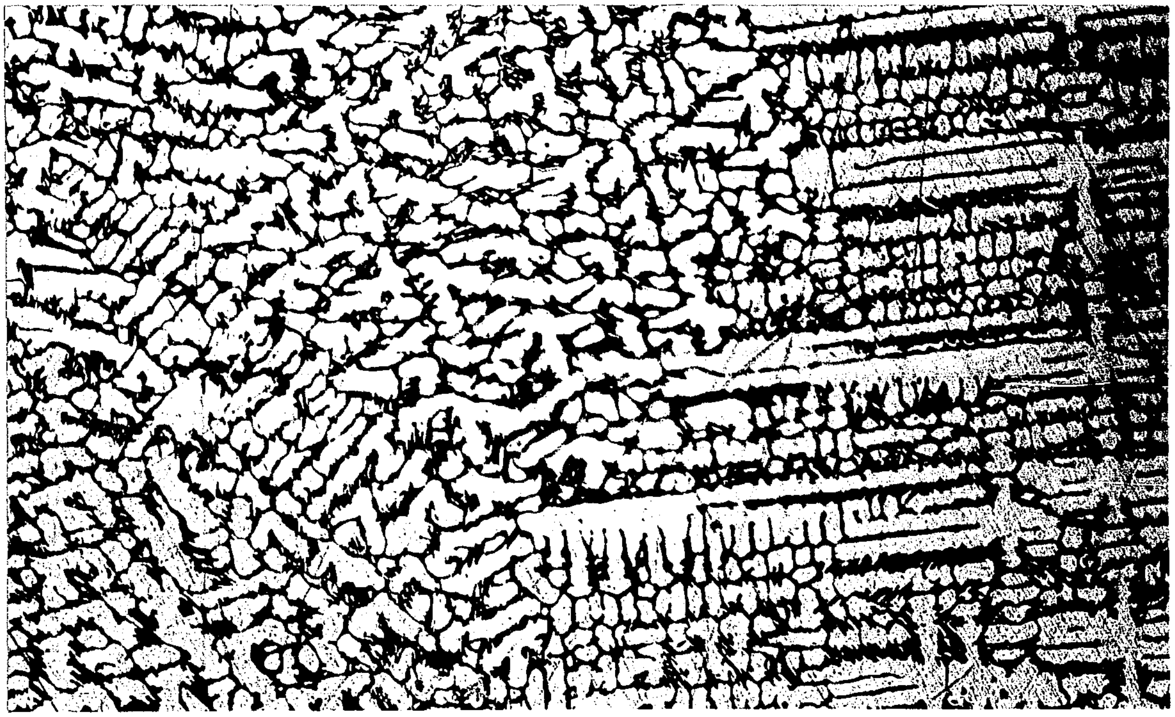

FIGURE 13. Microstructure of a cast alloy containing 2.26% Be-2.09% Al- 95.60% Cu.
Etch: Ferric Chloride Magnification:100X

FIGURE 14. Same spot as FIGURE 13. Magnification: 250X

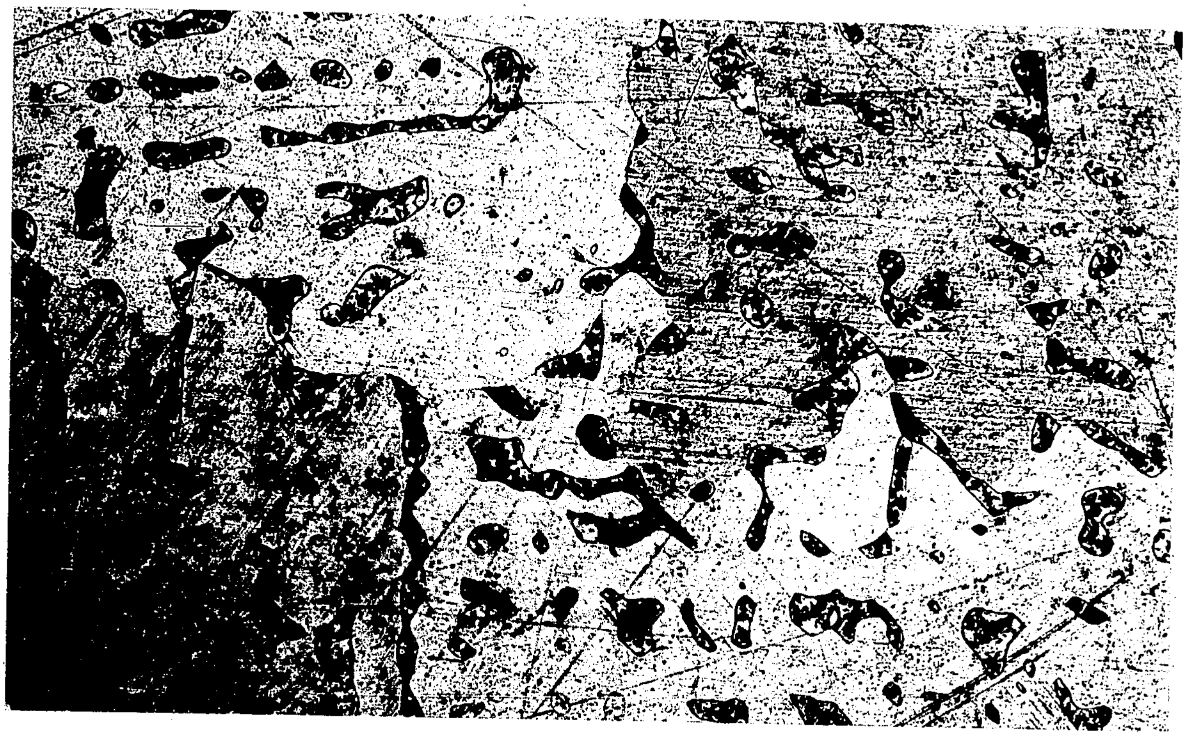

FIGURE 15. Microstructure of a cast and solution heat-treated alloy containing 2.25% Be- 0.03% Al- 97.63% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 16. Same spot as FIGURE 15. Magnification: 250X

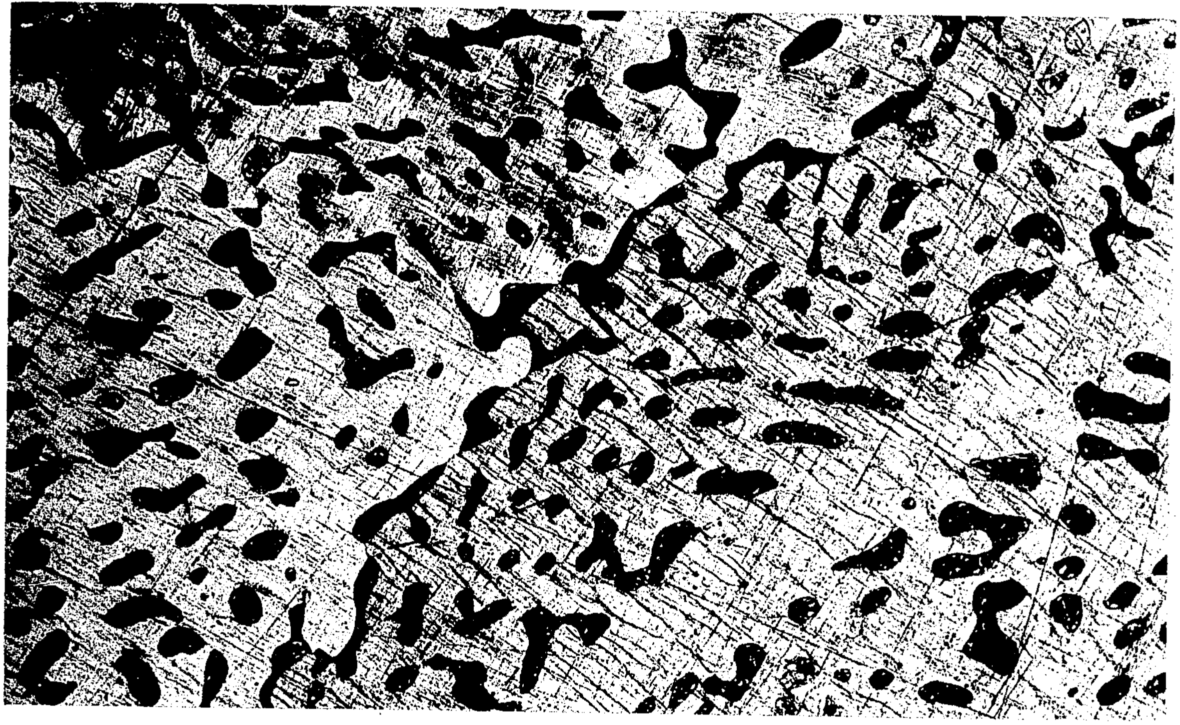

FIGURE 17. Microstructure of a cast and solution heat-treated alloy containing 2.26% Be- 0.60% Al- 97.12% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 18. Same spot as FIGURE 17. Magnification: 250X

FIGURE 19. Microstructure of a cast and solution heat-treated alloy containing 2.18% Be- 1.07% Al- 96.69% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 20. Same spot as FIGURE 19. Magnification: 250X

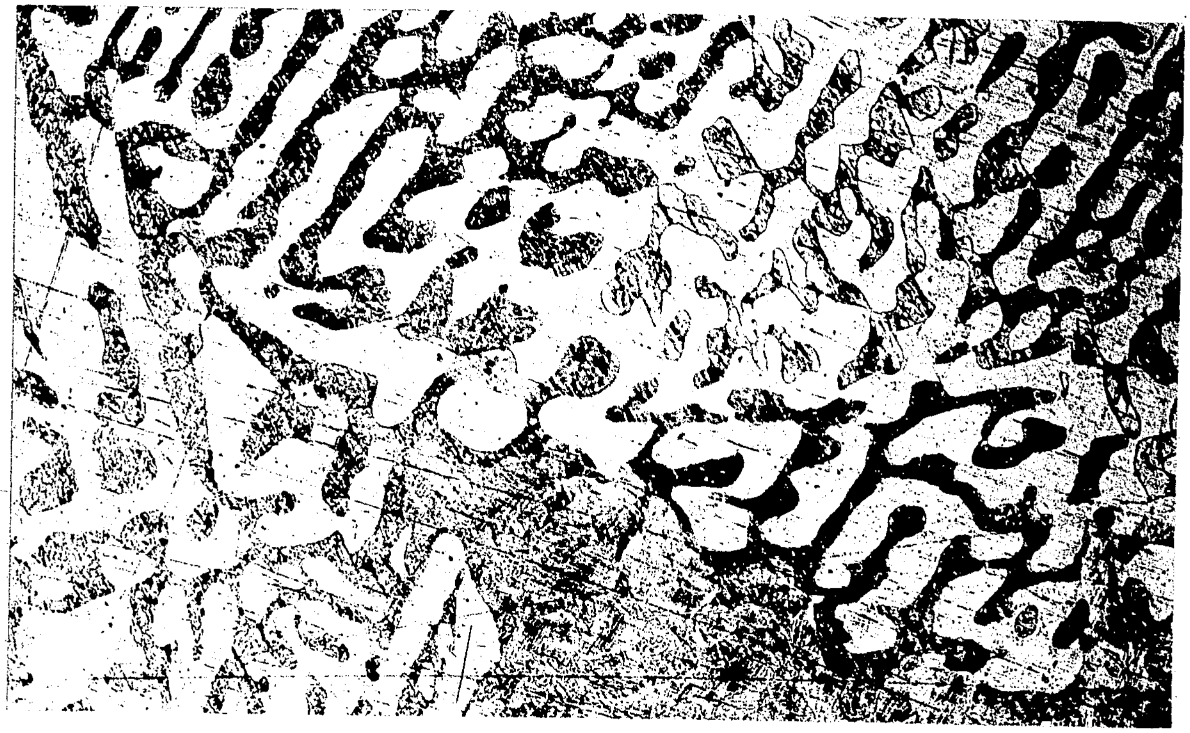

FIGURE 21. Microstructure of a cast and solution heat-treated alloy containing 2.26% Be- 2.09% Al- 95.60% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 22. Same spot as FIGURE 21. Magnification: 250X

FIGURE 23. Microstructure of a cast, solution heat-treated and aged alloy containing 2.25% Be- 0.03% Al- 97.63% Cu.
Etch: Ferric Chloride Magnification: 100X

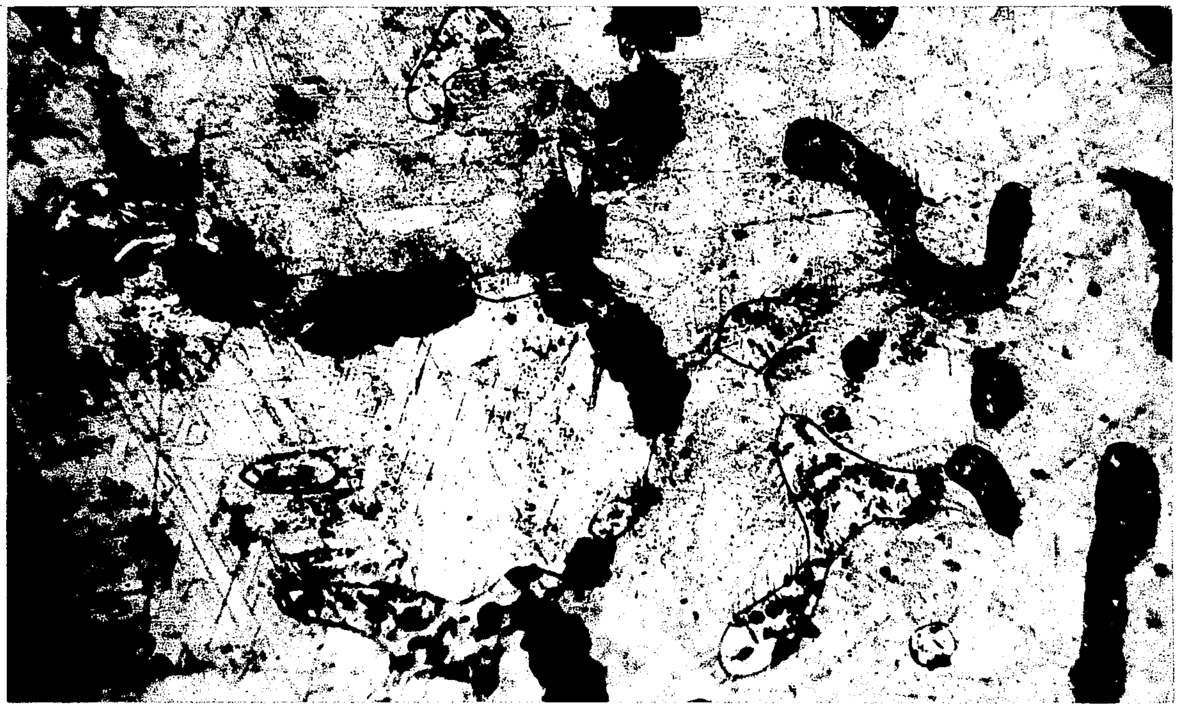

FIGURE 24. Same spot as FIGURE 23. Magnification: 250X

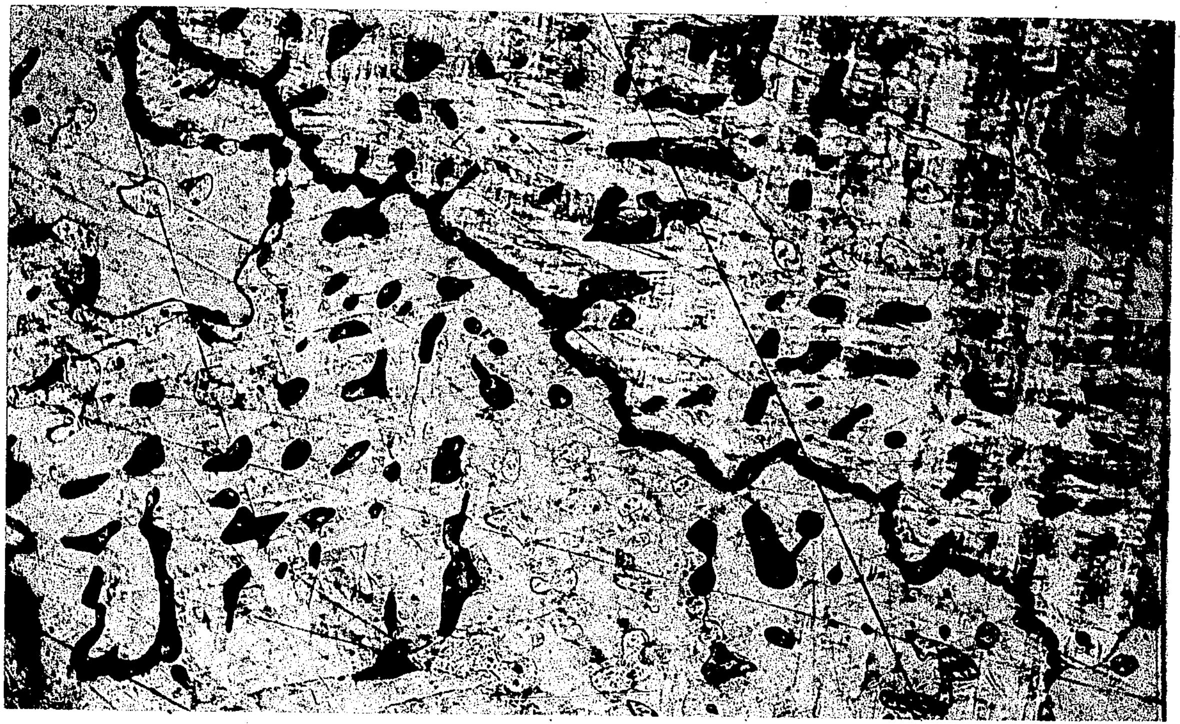

FIGURE 25. Microstructure of a cast, solution heat-treated and aged alloy containing 2.26% Be- 0.60% Al- 97.12% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 26. Same spot as Figure 25. Magnification: 250X

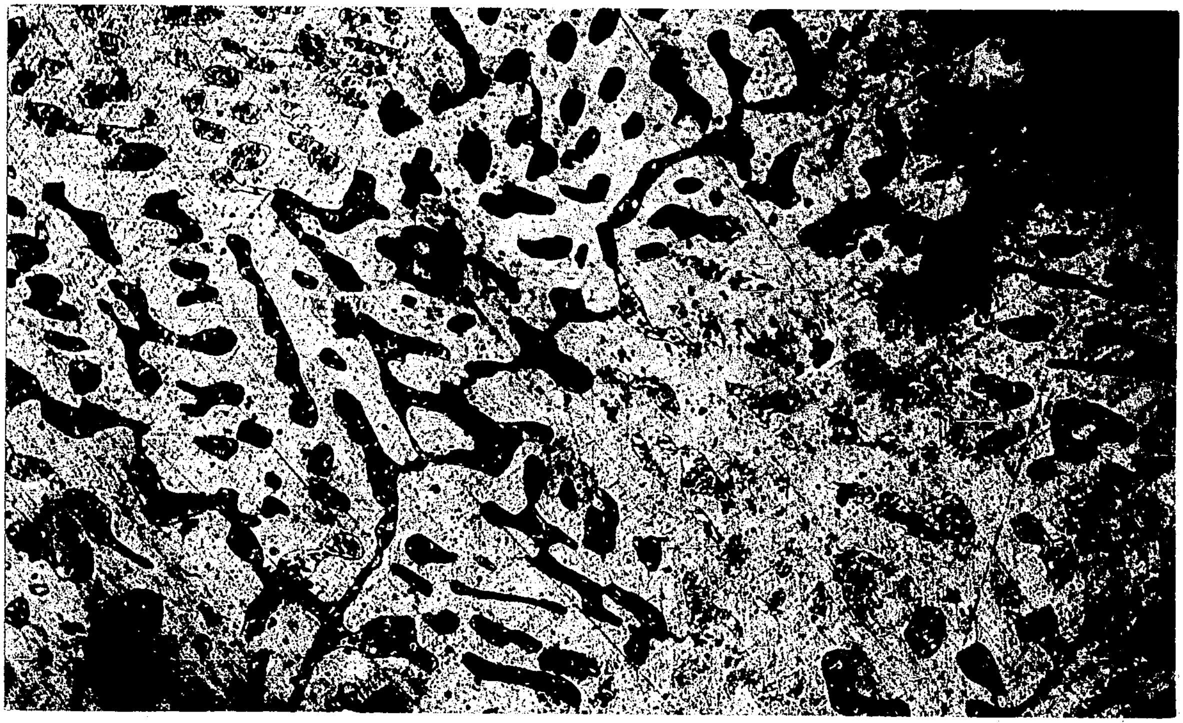

FIGURE 27. Microstructure of a cast, solution heat-treated and aged alloy containing 2.18% Be- 1.07% Al- 96.69% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 28. Same spot as FIGURE 27. Magnification: 250X

FIGURE 29. Microstructure of a cast, solution heat-treated and aged alloy containing 2.26% Be- 2.09% Al- 95.60% Cu.
Etch: Ferric Chloride Magnification: 100X

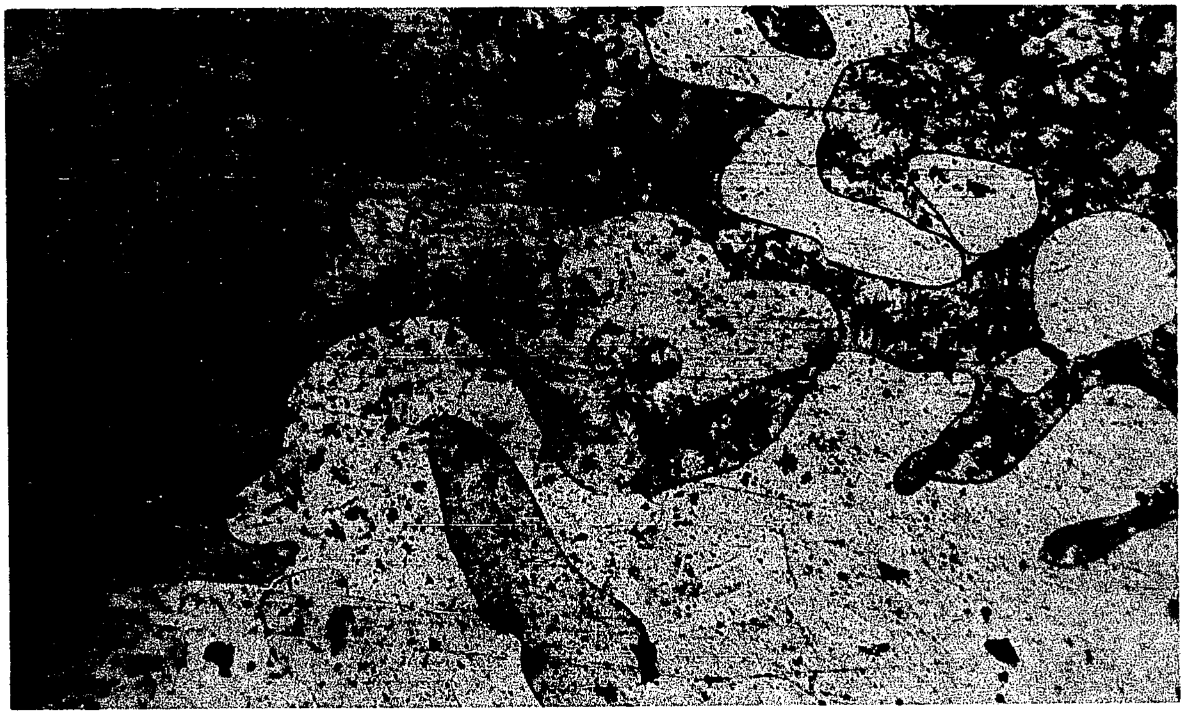

FIGURE 30. Same spot as FIGURE 29. Magnification: 250X

PART II

IRON ADDITIONS

An inspection of the iron-copper equilibrium systems shows that the diagram is of the age hardenable type in the range in which the iron is to be added to the alloys. The addition of iron should, then, produce results which are similar to those produced by the addition of cobalt to a binary alloy. This hypothesis led to the collection of the physical property data and photomicrographs as previously mentioned.

Table II shows the data obtained on the physical properties of the various alloys. The tabulated data is shown in graphical form in Figures 32 through 36. It should be noted that the hardness and tensile strength increase to a maximum at approximately 0.75% iron and then decreases as the iron content is further increased. The cast alloys, with no heat treatment, are so inhomogeneous as to make it difficult to obtain consistent data.

The cast and solution heat-treated beryllium-copper-iron alloys appear to have minimized the inhomogeneity as evidenced by the physical property data. There are several striking features which require notation. The most remarkable of these features is the marked increase elongation at approximately 0.75% iron. The tensile strength decreased below that of the cast alloys. However, the decrease followed the same trend as evidenced by the cast alloys, i.e., there was a maximum tensile strength at approximately 0.75% iron. The hardness values were somewhat inconsistent in that the hardness did not fall off in a regular fashion. The anomaly was explained by a determination of the grain size of the alloys. Optimum grain refinement was evidenced in the alloy containing approximately 0.75% iron.

The cast, solution heat-treated and aged alloys again evidence remarkable changes in the physical properties. The most significant changes are in the tensile properties. The tensile strength increases with increasing iron iron content up to approximately 0.75% iron and then decreases to values ultimately lower than the binary alloy processed in exactly the same manner.

The maximum strength developed is about 10% greater than the binary alloy appropriately processed. The elongation decreases from a maximum of 40% for the cast and solution heat-treated alloys to values of less than 1%. This was to be expected in view of the fact that full hardening ($41R_c$) was obtained in all the alloys.

Typical microstructures are shown in Figures 37 through 61. There are striking changes in these microstructures and these changes serve to confirm the physical property data. It should be noted that the volume of the "beta-phase" is reduced by an amount proportional to the iron content in the cast alloys. In addition, there is an apparent optimum grain size established at 0.75% iron. There is no apparent precipitation of iron or iron alloys from solution until the optimum grain size is reached. At this composition, the iron or iron alloy begins to precipitate out in the form of small needles. As the iron content is increased, the needles grow in size and then coalesce into a fan-shaped pattern (see Figure 61). The presence of this pattern leads to a brittle fracture as was evidenced in the tensile test. This embrittlement leads to a decreasing tensile strength as compared to the tensile strength obtained by adding only 0.75% iron.

The cast and solution heat-treated alloys show a greater degree of uniformity in the microstructure. The "beta-phase" resulting from casting is almost completely dissolved and there exist an apparently homogeneous solid solution in which the iron or iron alloy exists in solution and in the precipitated form.

The cast, solution heat-treated and aged alloys exhibit microstructures not radically different from the binary alloys processed in the same fashion. The physical property data show that full hardening was obtained in all the alloys and the microstructure showed full hardening as evidenced by precipitation of the gamma phase at the grain boundaries. The volume of the precipitate was estimated to have decreased only very slightly which leads one to the conclusion that the iron must all be found in alpha phase. Therefore, nucleation must take place around the iron.

In contrast with aluminum, iron is found to exert a very beneficial effect when added in the correct proportion. The addition of approximately 0.75% iron to a 2.1+% beryllium-copper alloy causes the grain size to decrease to approximately 1/10 the size of the grains found in the binary alloy. The tensile strength and elongation are considerably greater than those found for the binary alloy. Addition of excessive amounts of iron are to be avoided by reason of the embrittlement incurred by such additions.

FIGURE 31. Microstructure of a cast alloy containing 2.16% Be-, 2.04% Fe, and 95.72% Cu.
Etch: Ferric Chloride Magnification: 100X

TABLE II — PHYSICAL PROPERTIES of Be-Cu-Fe ALLOYS

	AS CAST			CAST, SOLUTION HEAT-TREATED 72hrs. at 1525°F			CAST, SOLN. HEAT-TREATED and AGED 2.5hrs at 700°F		
PERCENT IRON IN ALLOY	Ultimate Tensile Strength	Elongation in 2 inches	Rockwell B Hardness	Ultimate Tensile Strength	Elongation in 2 inches	Rockwell B Hardness	Ultimate Tensile Strength	Elongation in 2 inches	Rockwell C Hardness
0.04%	55,000 p.s.i.	17.8%	76	50,800 p.s.i.	16.3%	74	111,000 p.s.i.	0.65%	41
0.11 %	58,000 p.s.i.	10.6%	76	54,500 p.s.i.	16.9%	68	111,700 p.s.i.	0.60%	41
0.24%	70,400 p.s.i.	15.3%	83	57,700 p.s.i.	25.6%	64	113,700 p.s.i.	0.65%	41
0.50%	73,300 p.s.i.	16.5	88	61,200 p.s.i.	33.6%	66	116,900 p.s.i.	0.70%	41
0.75%	71,200 p.s.i.	#	85	62,500 p.s.i.	40.2%	70	111,500 p.s.i.	0.75%	41
0.98%	72,200 p.s.i.	#	84	60,800 p.s.i.	37.6%	72	97,400 p.s.i.	0.75%	41
1.40%	76,100 p.s.i.	18.0%	82	57,300 p.s.i.	26.6%	66	108,400 p.s.i.	0.80%	41
2.04%	61,700 p.s.i.	#	83	44,300 p.s.i.	#	59	105,000 p.s.i.	0.08%	41

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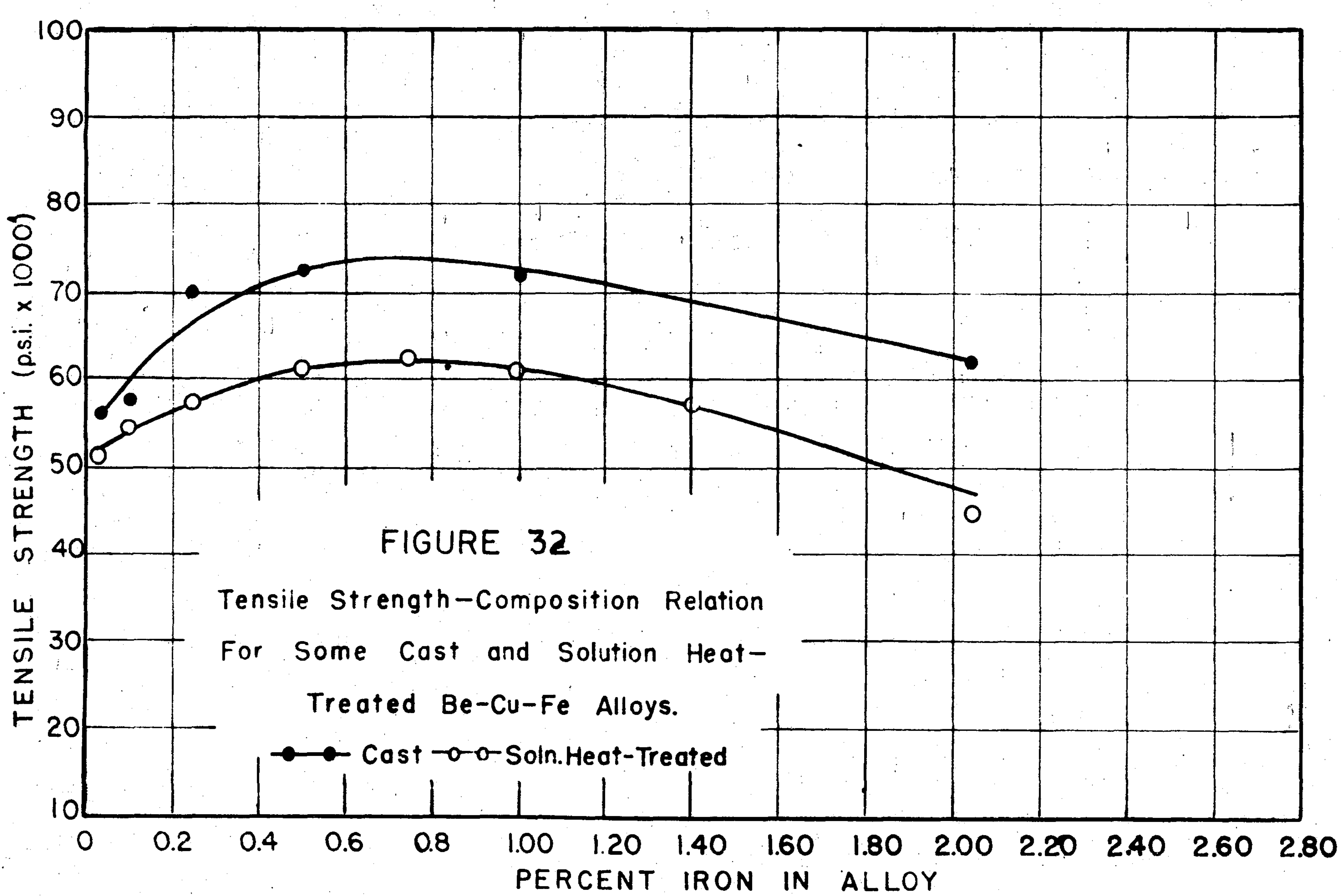

FIGURE 32

Tensile Strength—Composition Relation For Some Cast and Solution Heat-Treated Be-Cu-Fe Alloys.

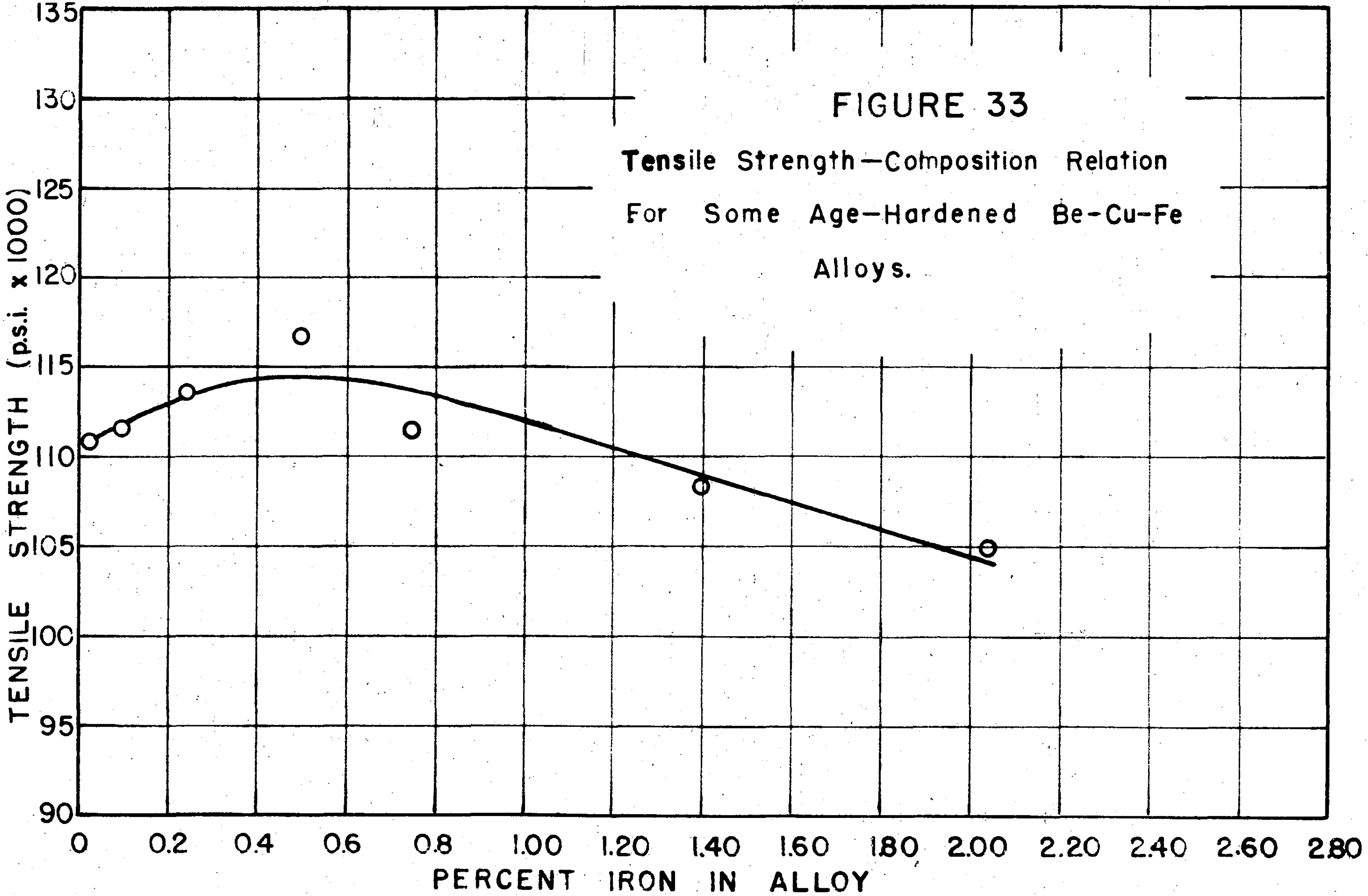

FIGURE 33

Tensile Strength—Composition Relation For Some Age-Hardened Be-Cu-Fe Alloys.

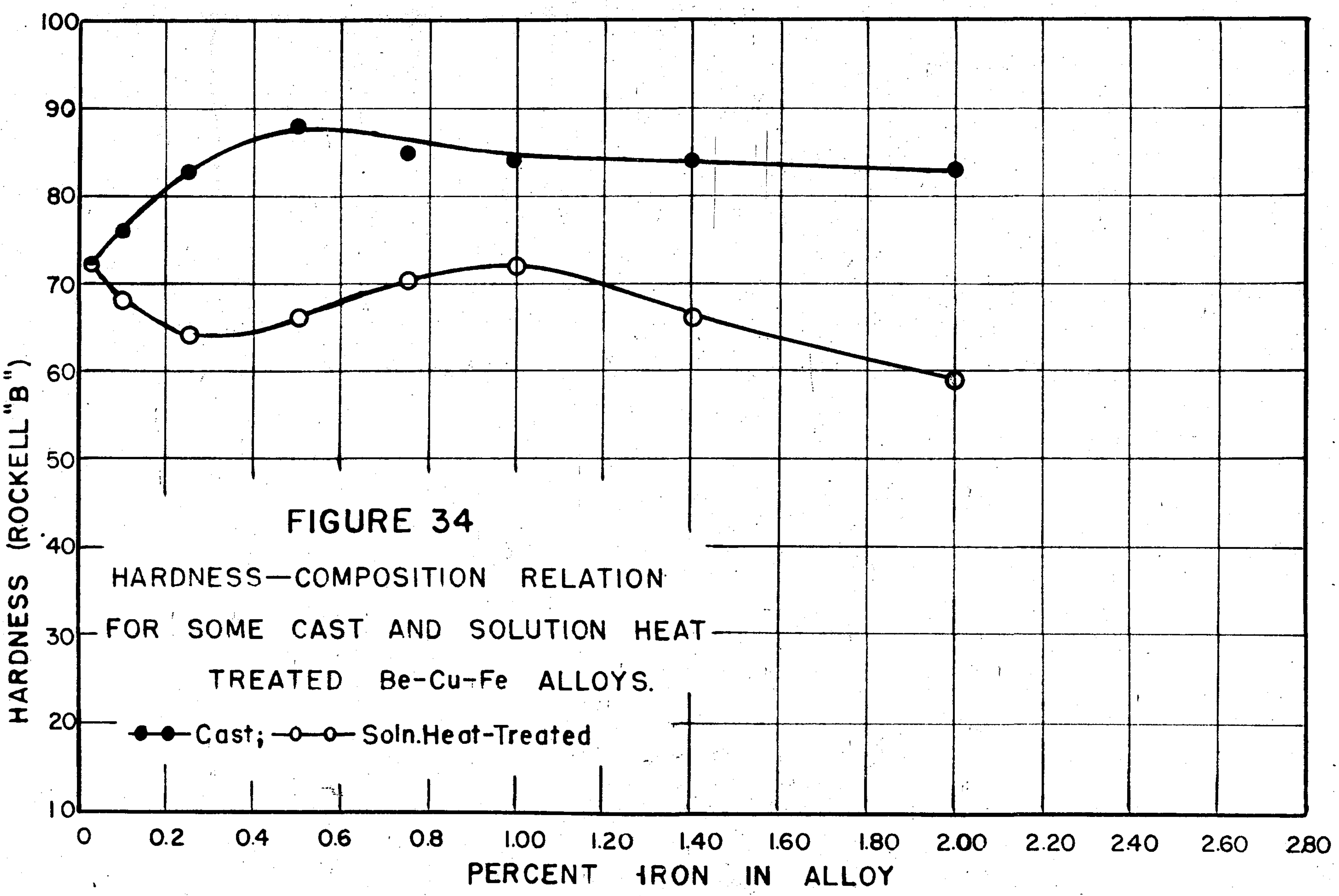

FIGURE 34

HARDNESS—COMPOSITION RELATION FOR SOME CAST AND SOLUTION HEAT TREATED Be-Cu-Fe ALLOYS.

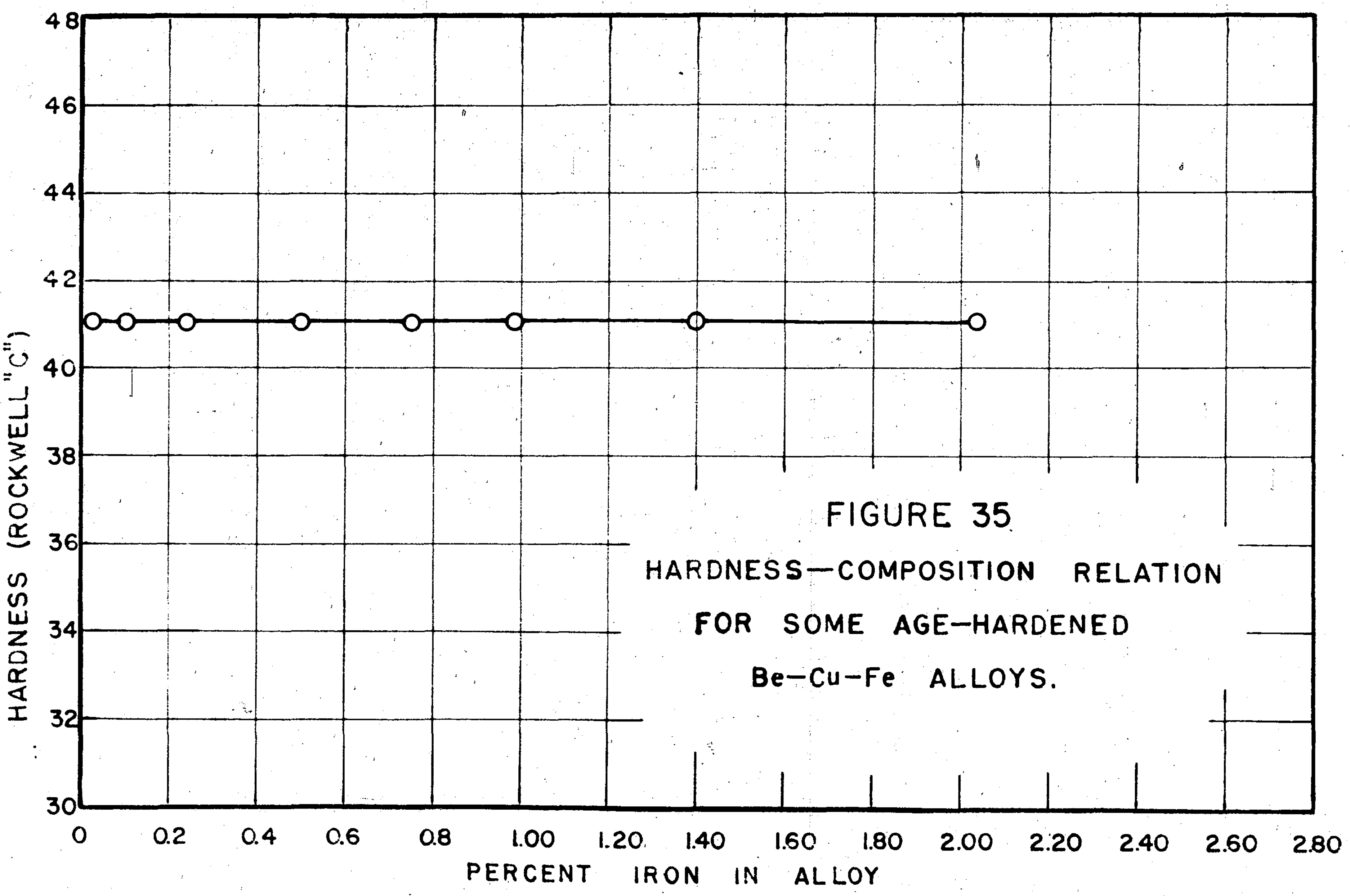

FIGURE 35

HARDNESS—COMPOSITION RELATION FOR SOME AGE-HARDENED Be-Cu-Fe ALLOYS.

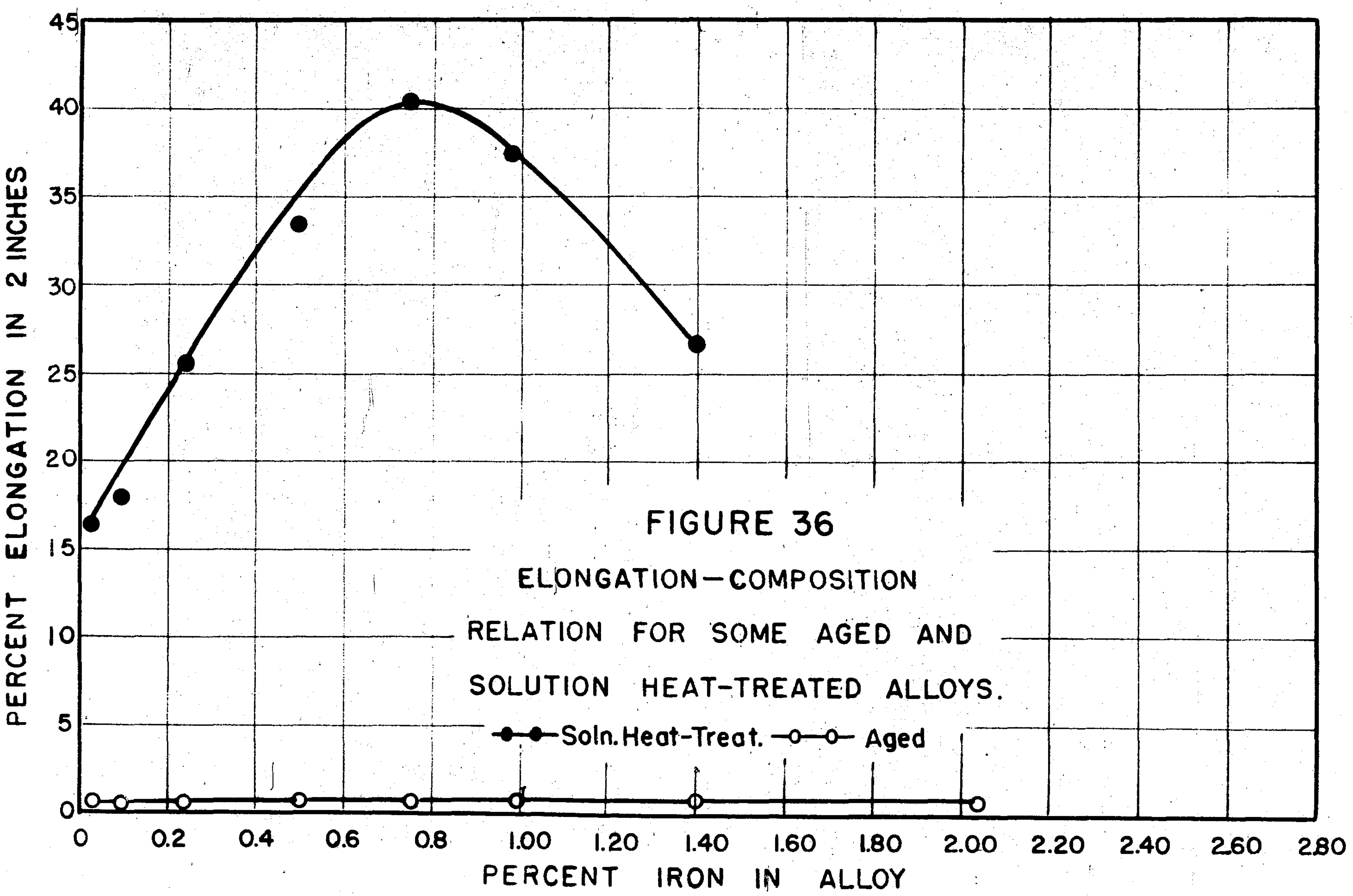

FIGURE 36

ELONGATION—COMPOSITION RELATION FOR SOME AGED AND SOLUTION HEAT-TREATED ALLOYS.

FIGURE 37. Microstructure of a cast alloy containing 2.25% Be-0.04% Fe- 97.63% Cu.
Etch: Ferric Chloride Magnification: 100X

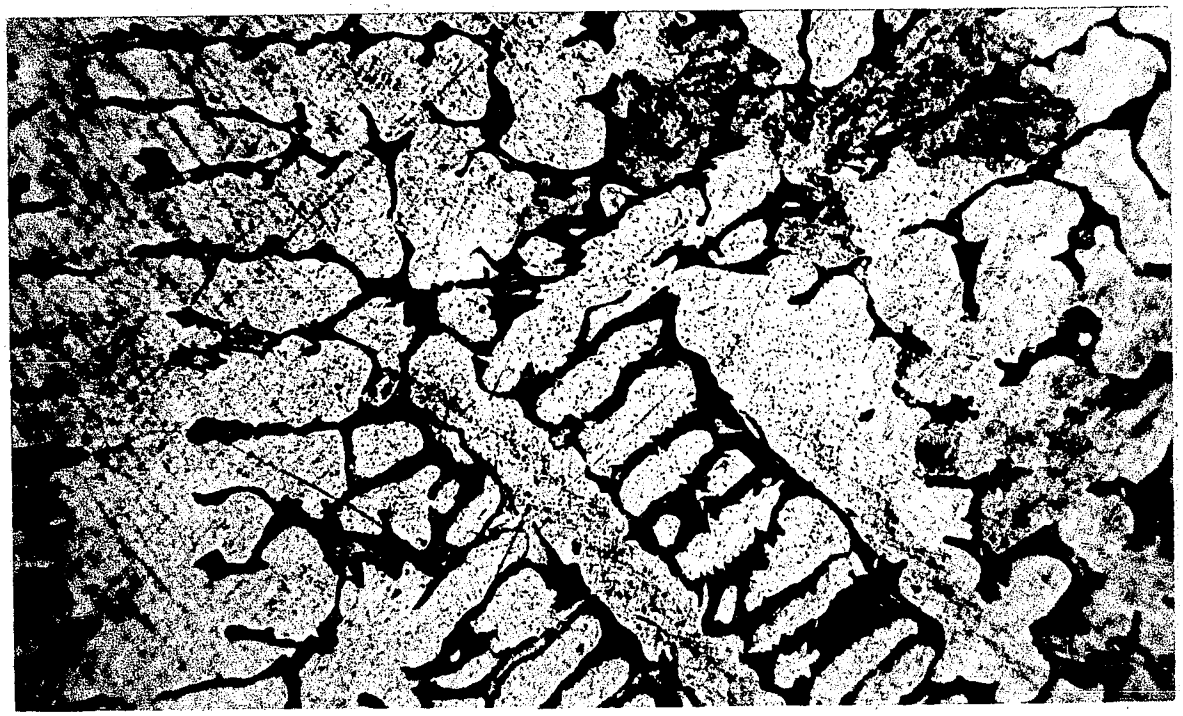

FIGURE 38. Same spot as FIGURE 37. Magnification: 250X

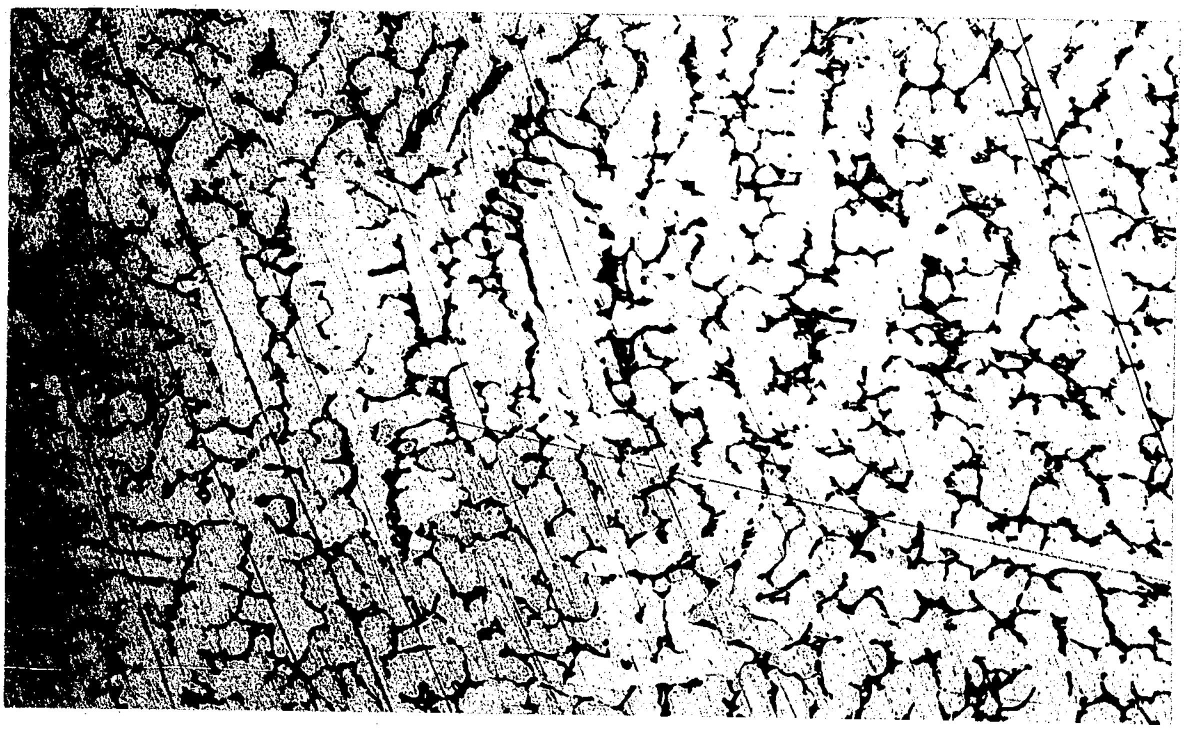

FIGURE 39. Microstructure of a cast alloy containing 2.15% Be-0.50% Fe - 97.29% Cu.
Etch: Ferric Chloride Magnification: 100X

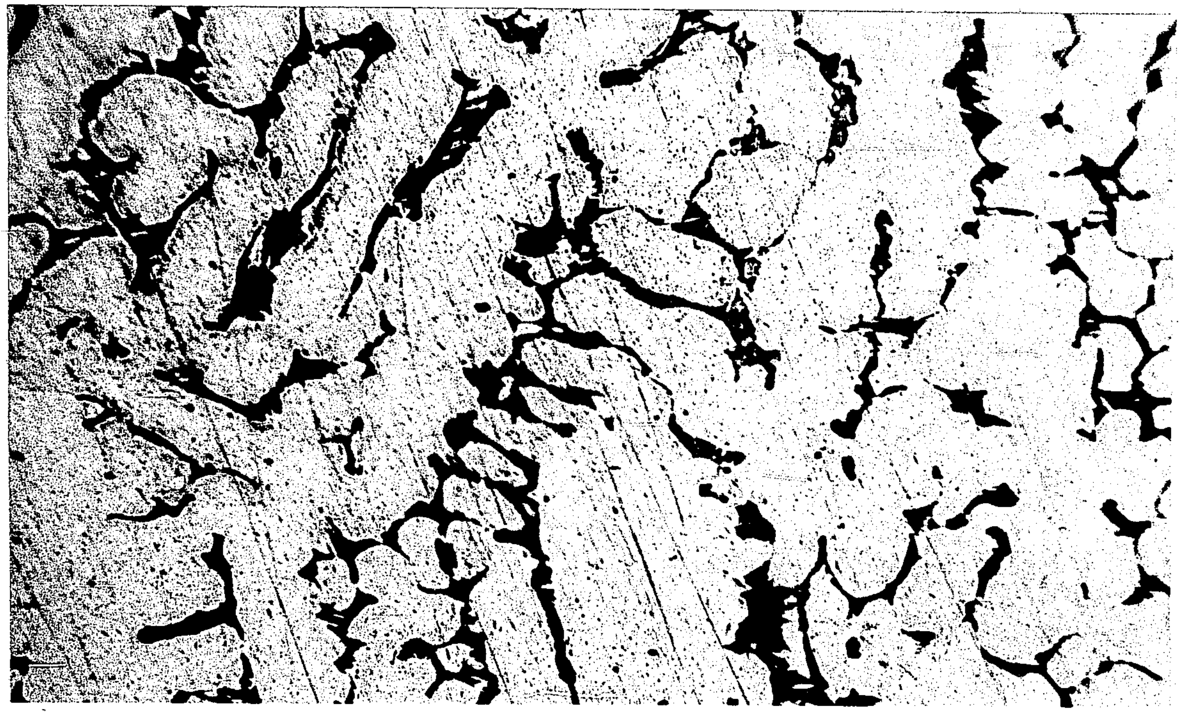

FIGURE 40. Same spot as FIGURE 39. Magnification: 250X

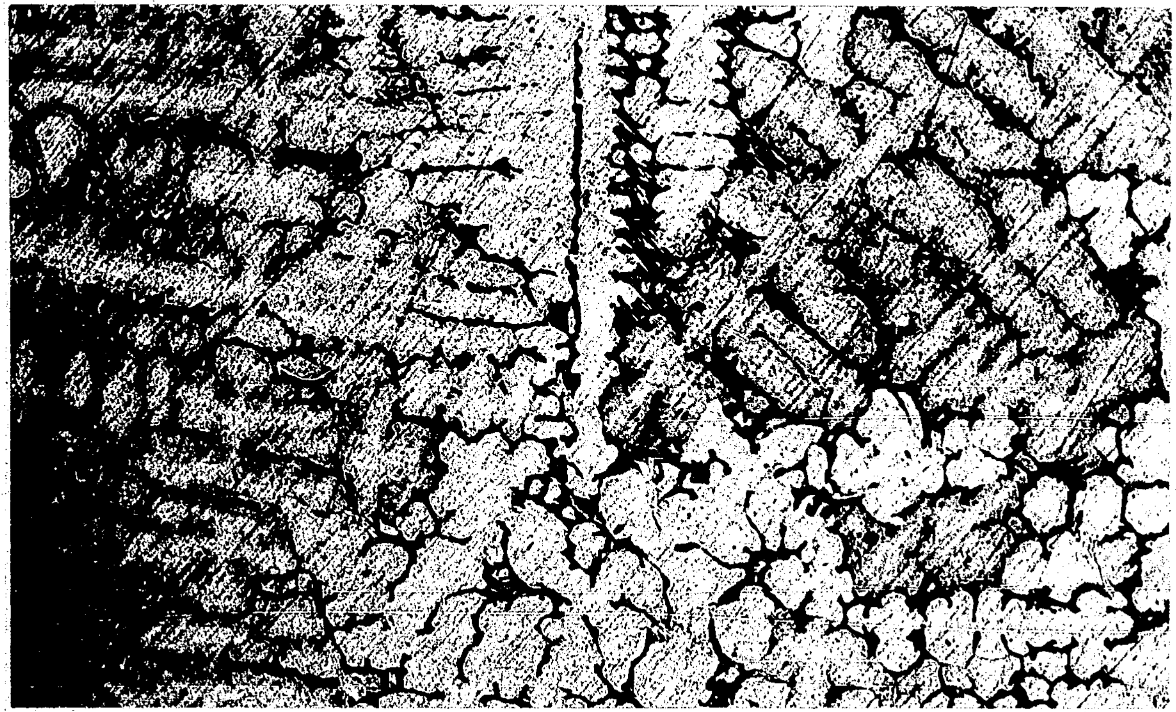

FIGURE 41. Microstructure of a cast alloy containing 2.09% Be-0.98% Fe - 96.85% Cu.
Etch: Ferric Chloride Magnification: 100X

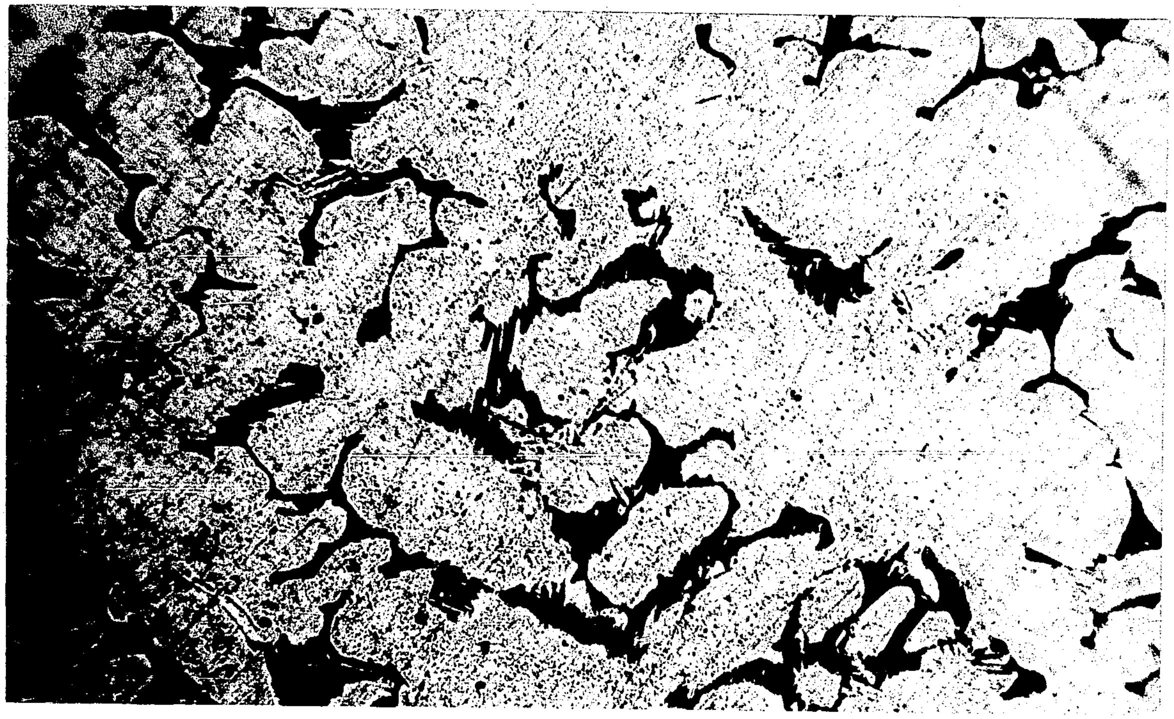

FIGURE 42. Same spot as FIGURE 41. Magnification: 250X

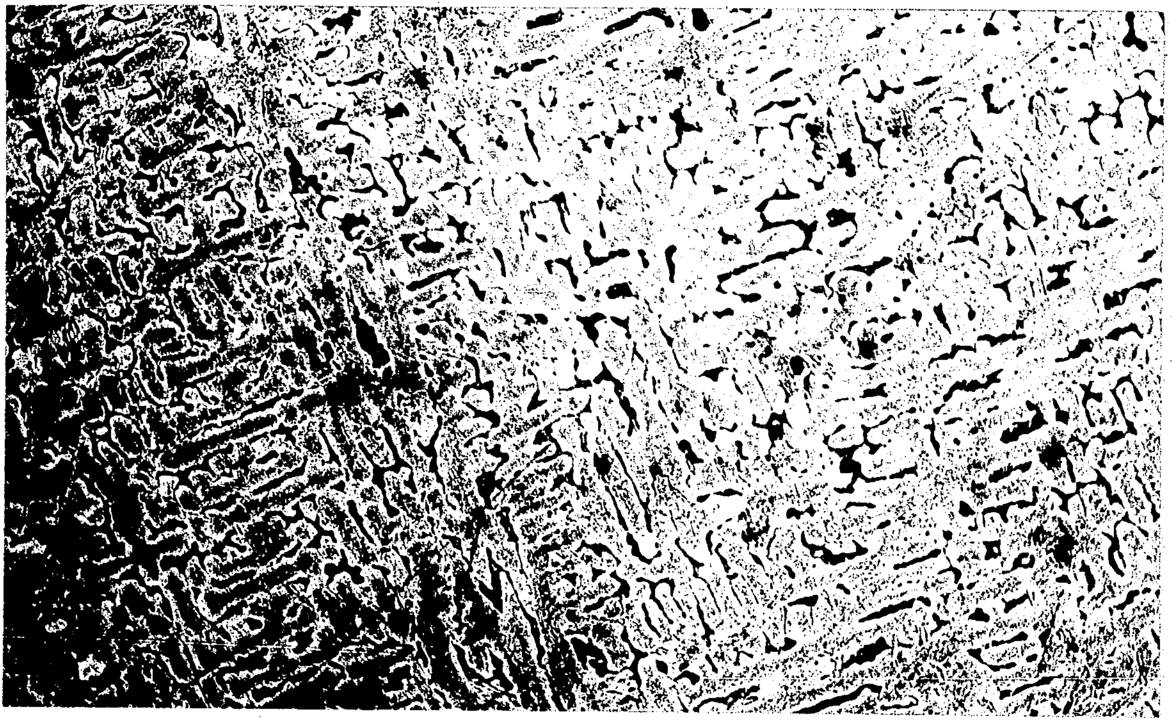

FIGURE 43. Microstructure of a cast alloy containing 2.16% Be-2.04% Fe- 95.72% Cu.
Etch: Ferric Chloride Magnification: 100X

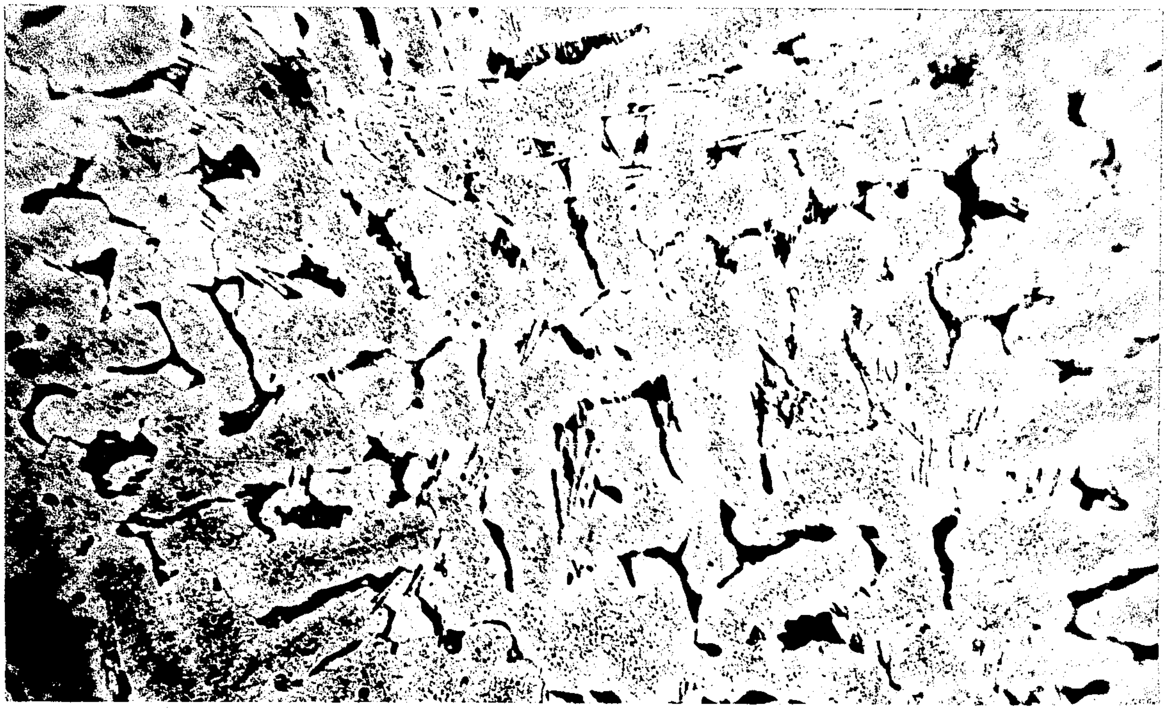

FIGURE 44. Same spot as FIGURE 43. Magnification: 250X

FIGURE 45. Microstructure of a cast and solution heat-~~treated~~ alloy containing 2.25% Be- 0.04% Fe- 97.63% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 46. Same spot as FIGURE 45. Magnification: 250X

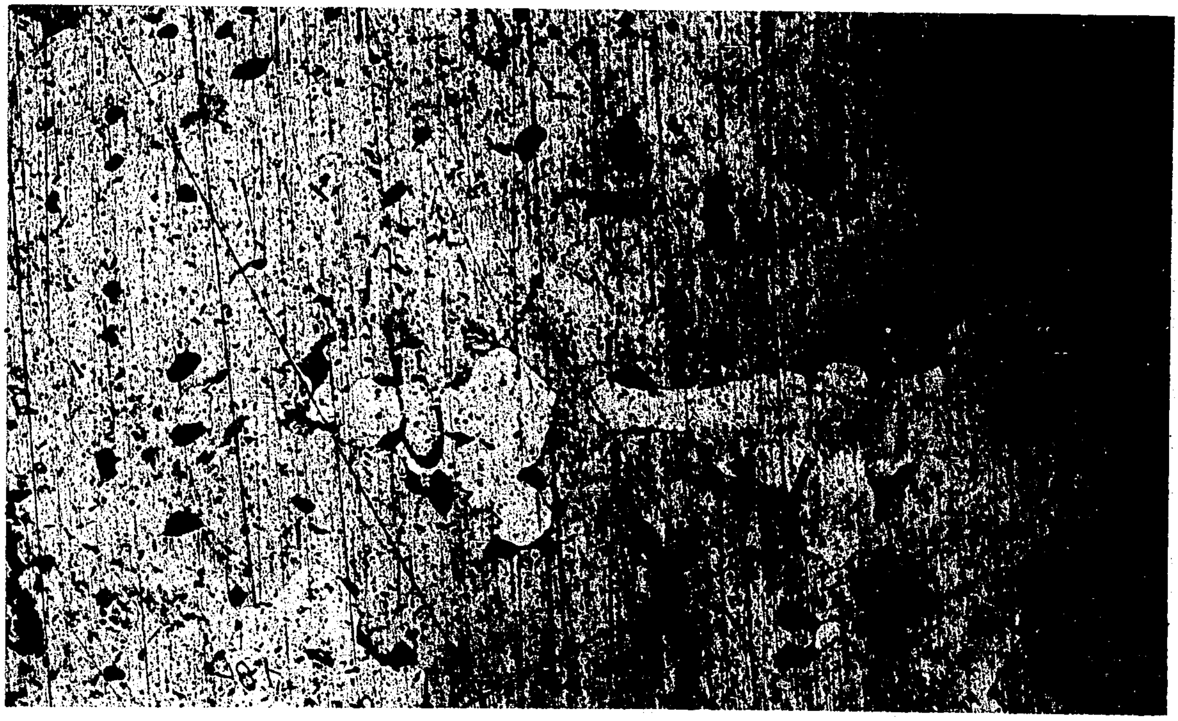

FIGURE 47. Microstructure of a cast and solution heat-treated alloy containing 2.15% Be- 0.50% Fe- 97.29% Cu.
Etch: Ferric Chloride Magnification: 110X

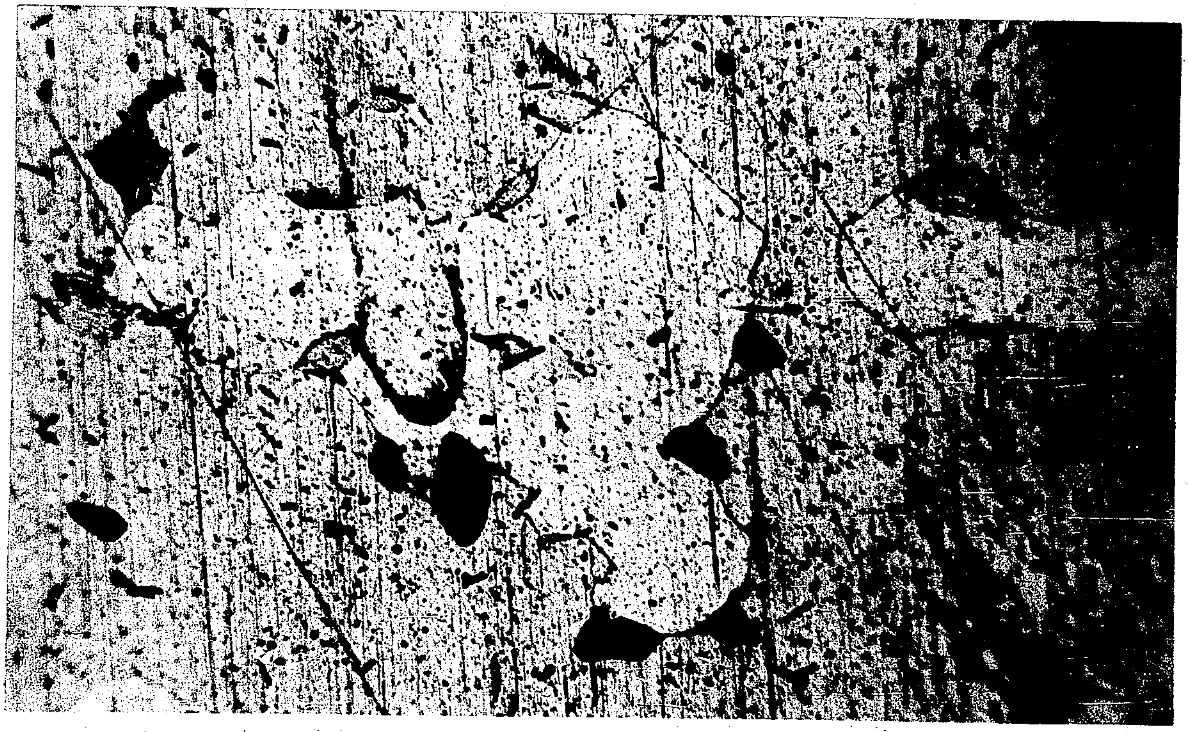

FIGURE 48. Same spot as FIGURE 47. Magnification: 250X

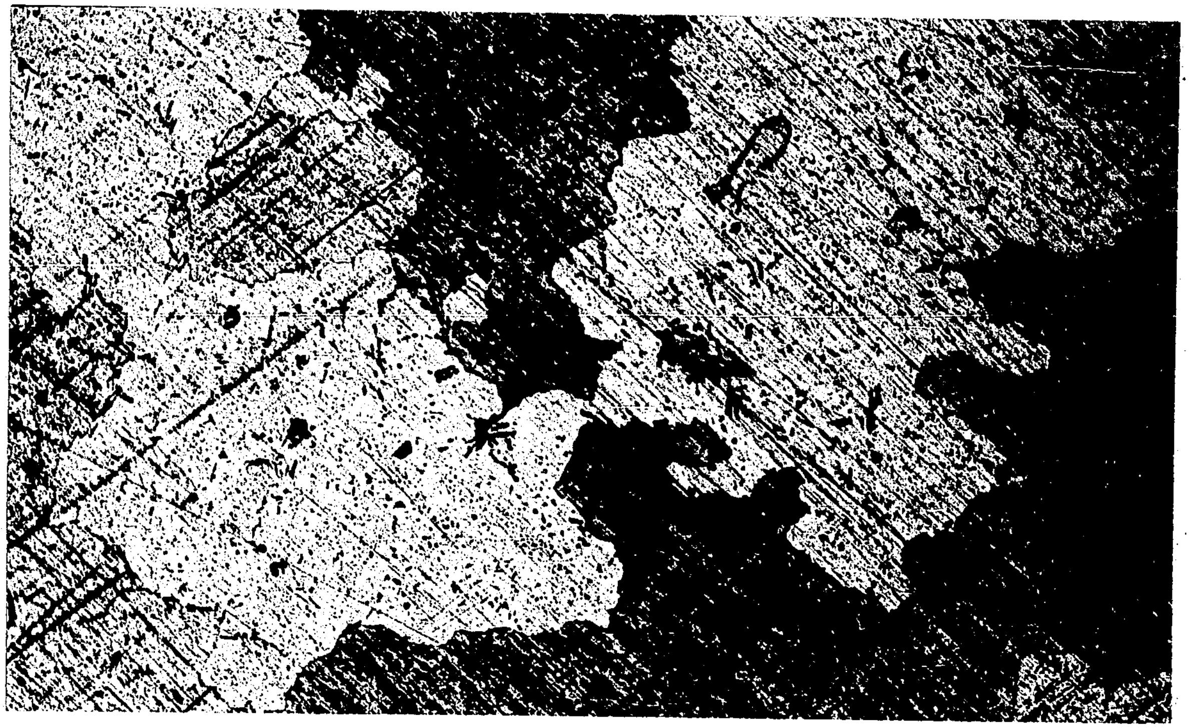

FIGURE 49. Microstructure of a cast and solution heat-treated alloy containing 2.09% Be- 0.98% Fe- 96.85% Cu.
Etch: Ferric Chloride Magnification: 100X

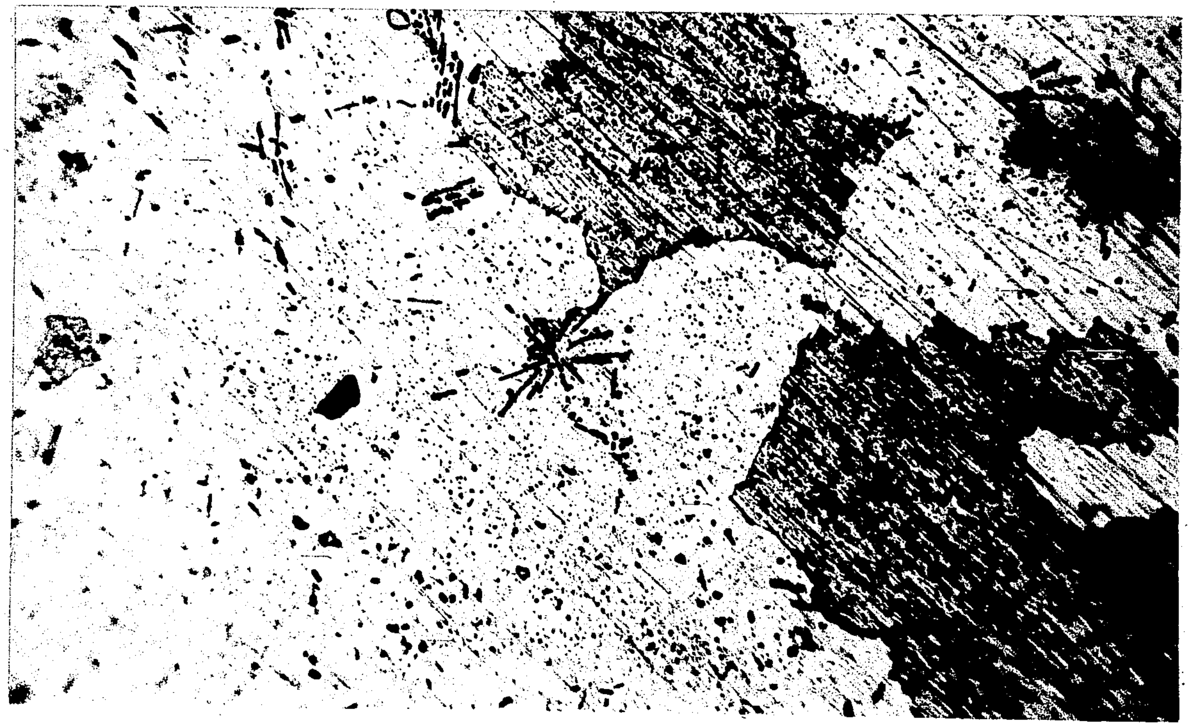

FIGURE 50. Same spot as FIGURE 49. Magnification: 250X

FIGURE 51. Microstructure of a cast and solution heat-treated alloy containing 2.16% Be- 2.04% Fe- 95.72% Cu.
Etch: Ferric Chloride Magnification: 100X

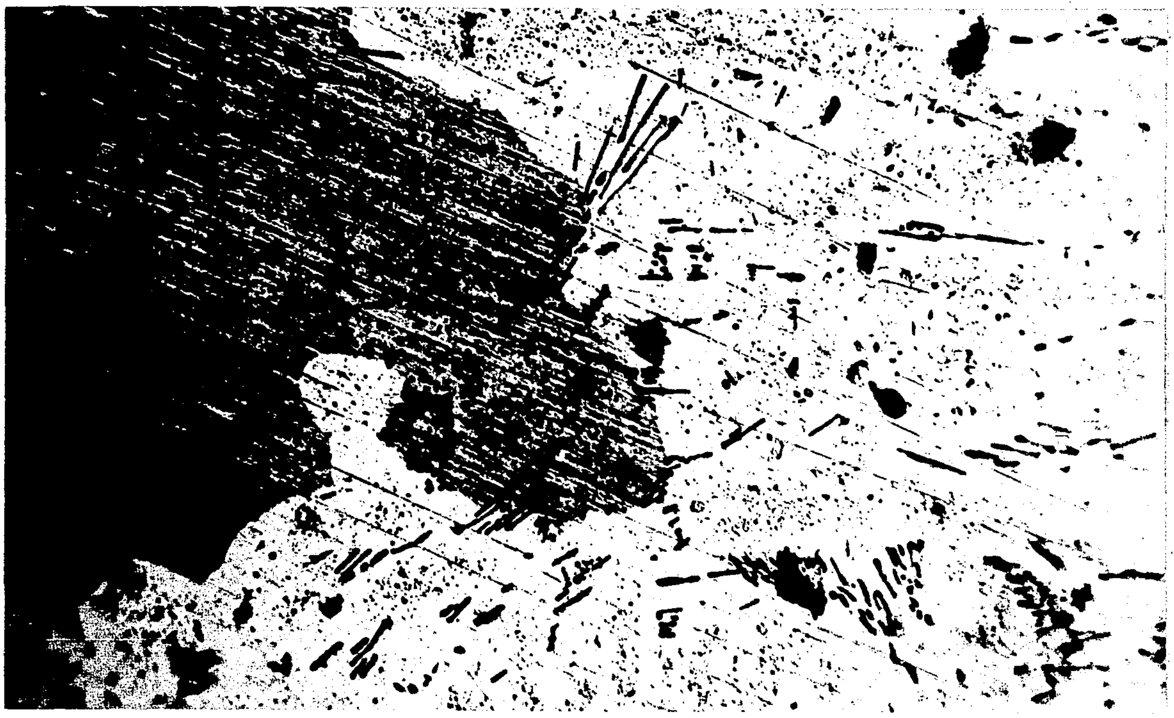

FIGURE 52. Same spot as FIGURE 51. Magnification: 250X

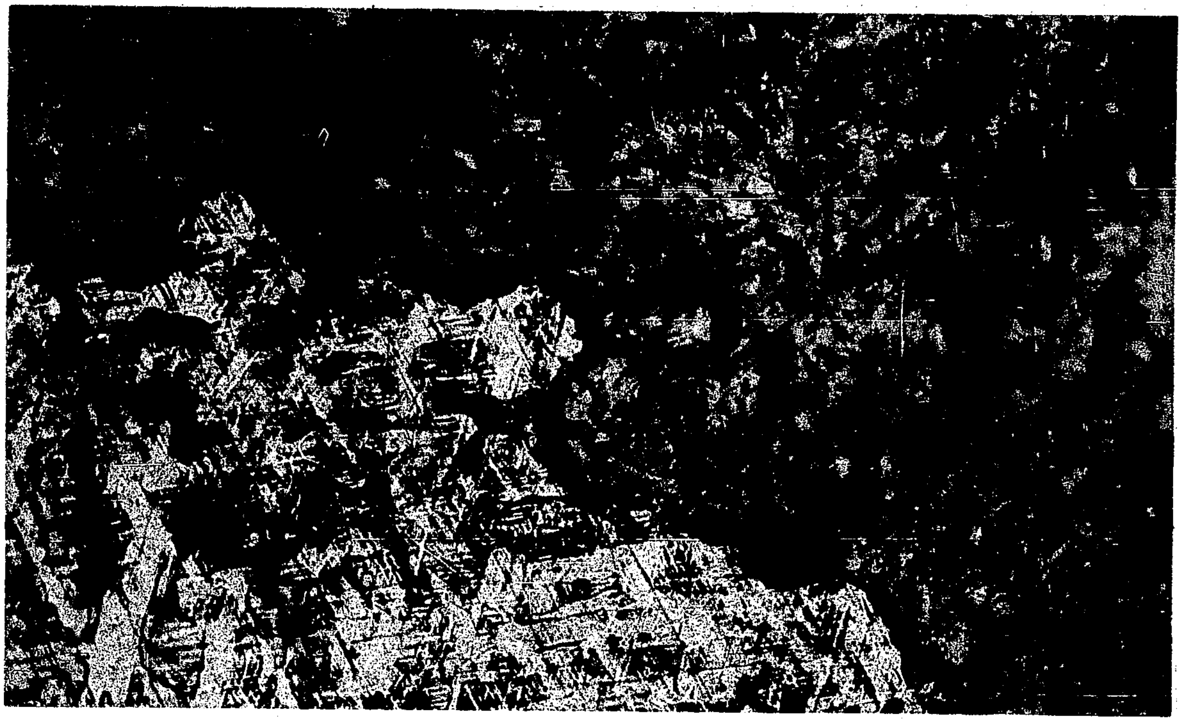

FIGURE 53. Microstructure of a cast, solution heat-treated and aged alloy containing 2.25% Be- 0.04% Fe- 97.63% Cu.
Etch: Ferric Chloride Magnification: 100X

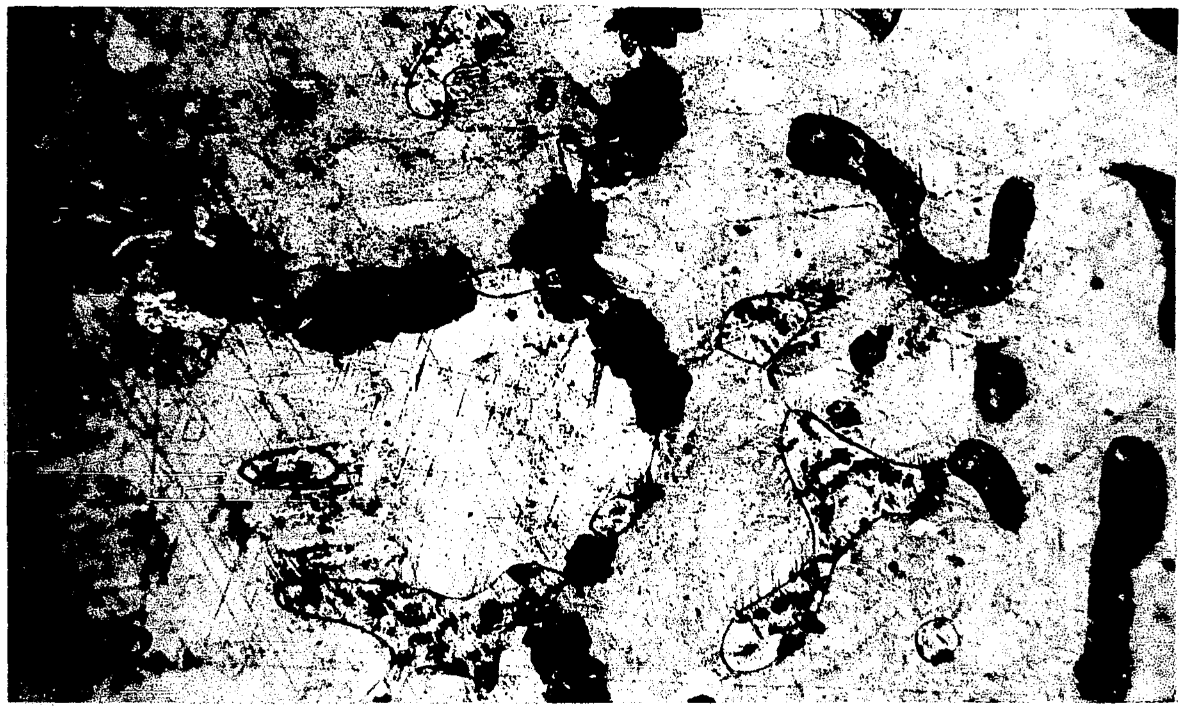

FIGURE 54. Same spot as FIGURE 53. Magnification: 250X

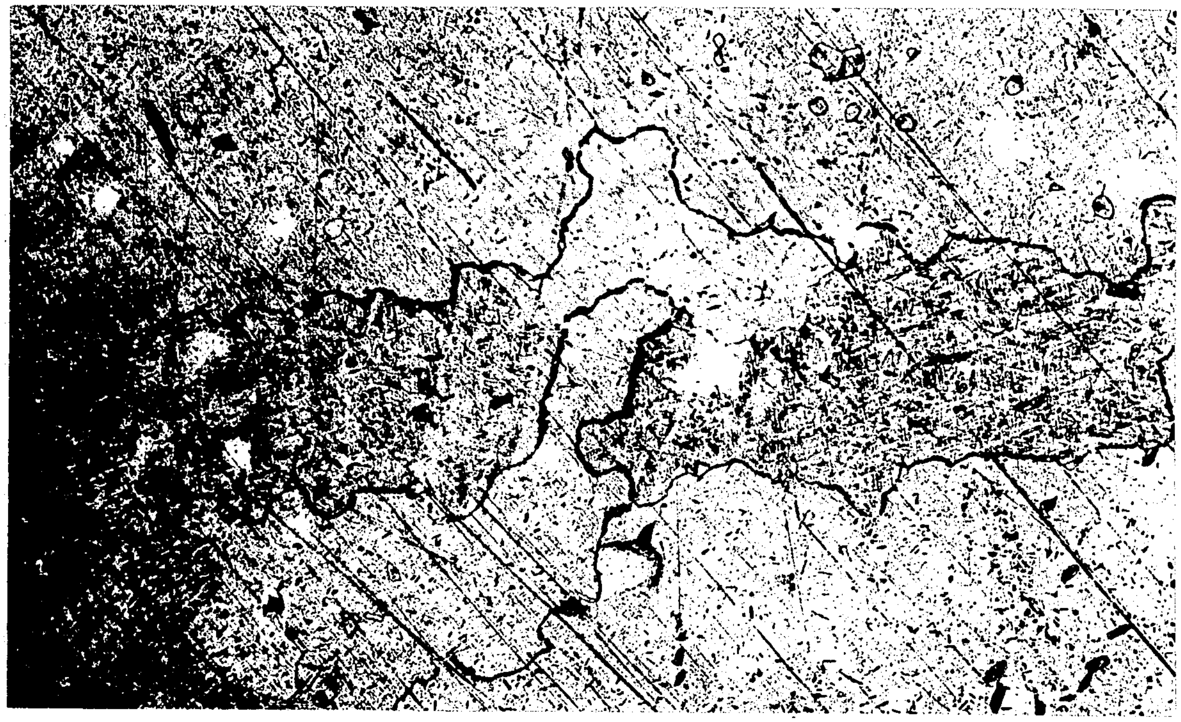

FIGURE 55. Microstructure of a cast, solution heat-treated and aged alloy containing 2.15% Be- 0.50% Fe- 97.29% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 56. Same spot as FIGURE 55. Magnification: 250X

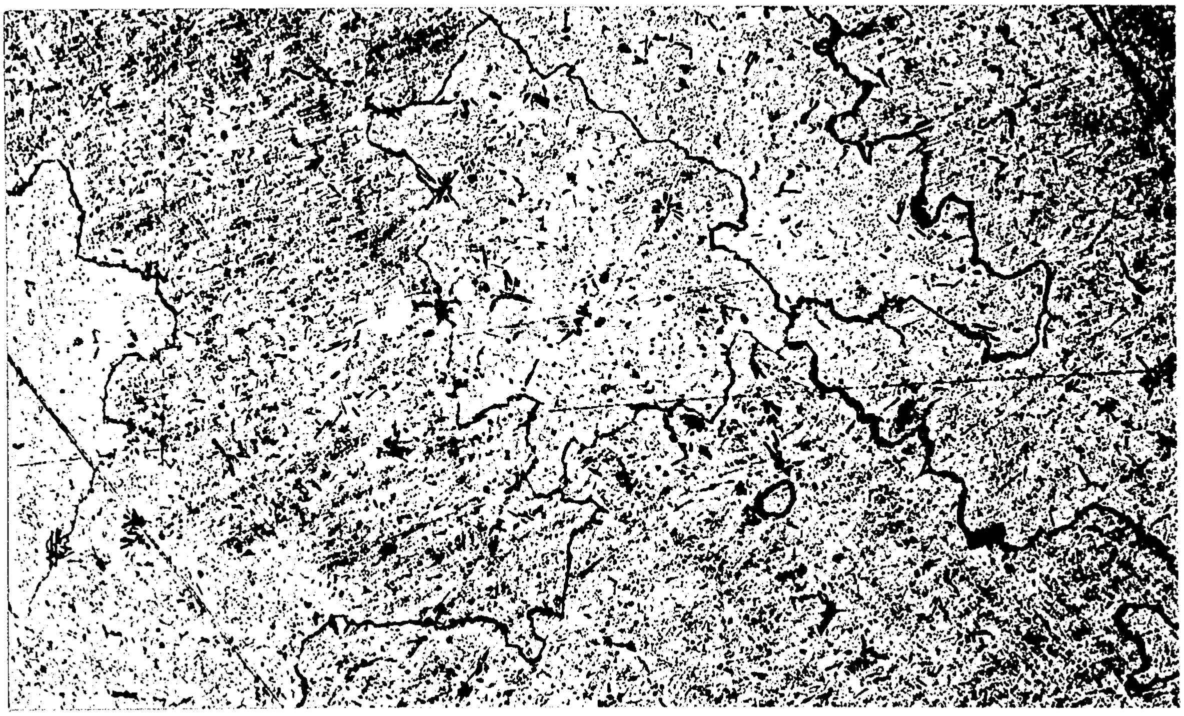

FIGURE 57. Microstructure of a cast, solution heat-treated and aged alloy containing 2.09% Be-0.98% Fe- 96.85% Cu.
Etch: Ferric Chloride Magnification: 100X

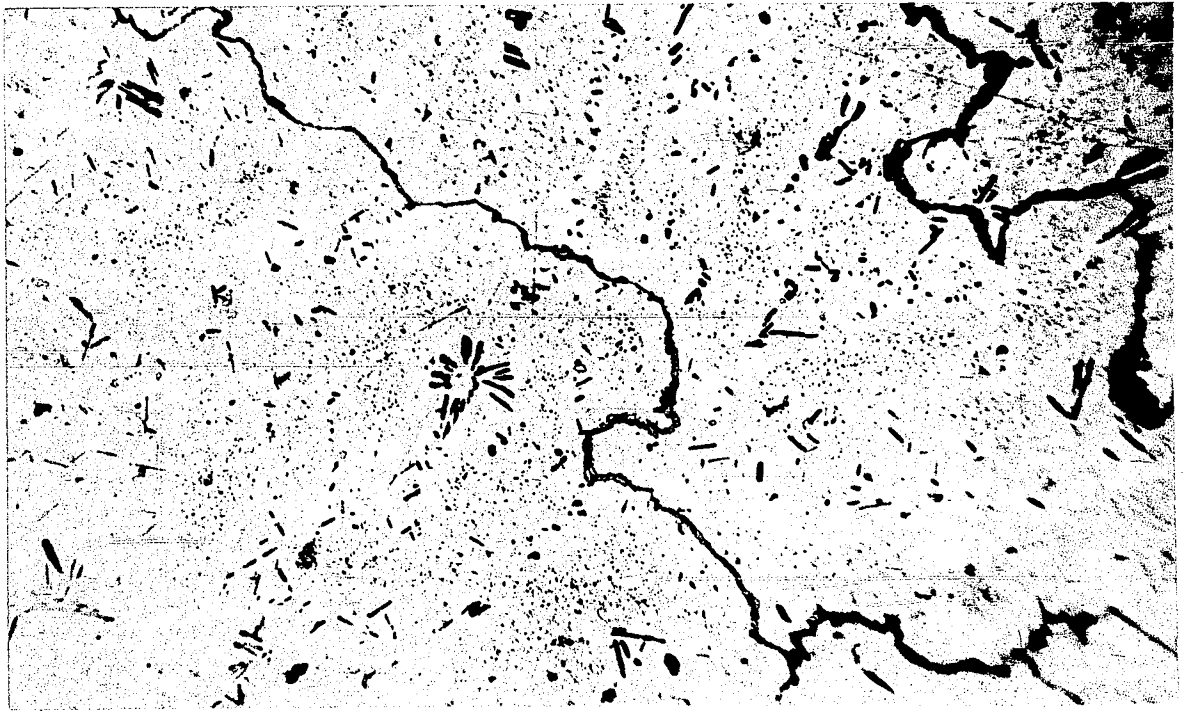

FIGURE 58. Same spot as FIGURE 57. Magnification: 250X

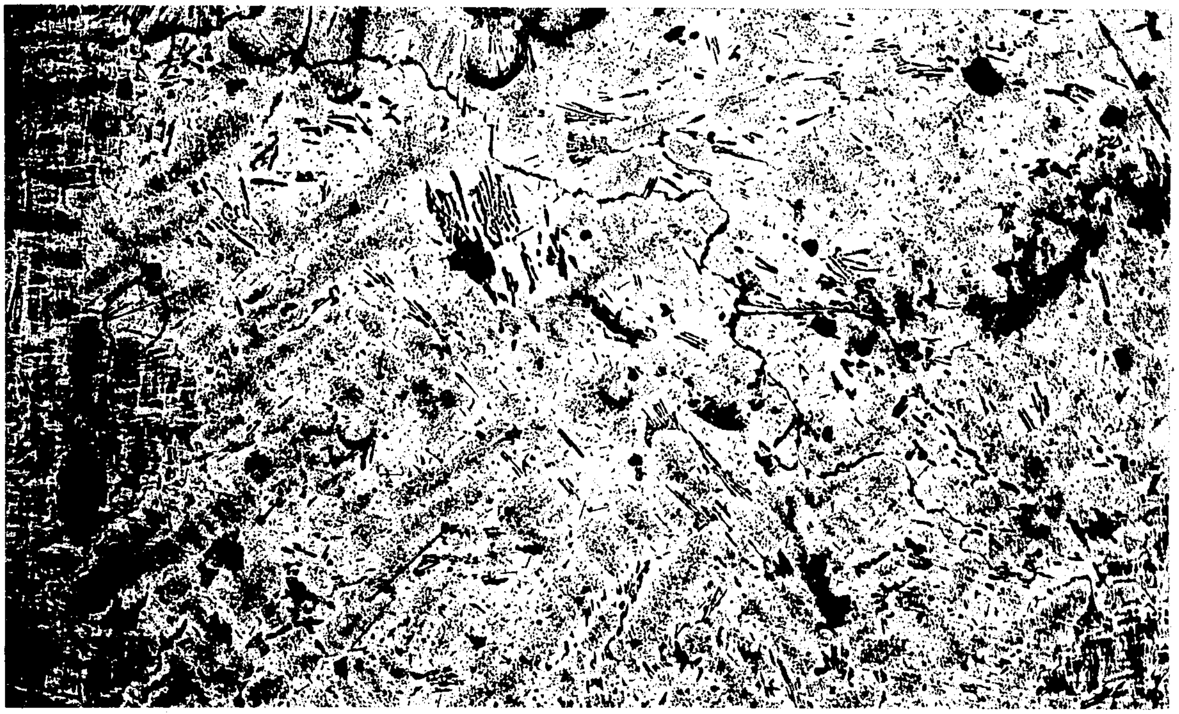

FIGURE 59. Microstructure of a cast, solution heat-treated and aged alloy containing 2.16% Be- 2.04% Fe- 95.72% Cu.
Etch: Ferric Chloride Magnification: 100X

FIGURE 60. Same spot as FIGURE 59. Magnification: 250X

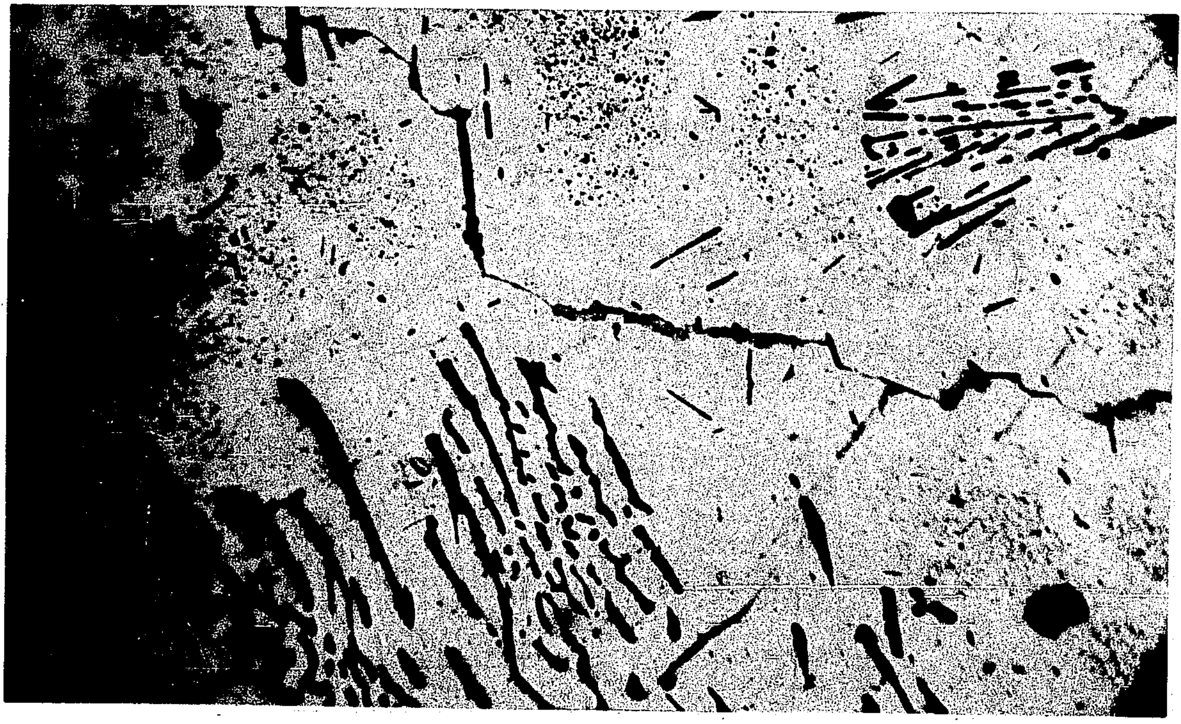

FIGURE 61.   Same spot as FIGURE 59.   Magnification: 500X

SUMMARY

Inspection of the tabulated and graphical data and photomicrographs shows that aluminum exerts a detrimental effect when added to cast beryllium-copper alloys in appreciable amounts. Such additions are detrimental in that they prevent the alloy from being fully hardened and because they promote grain growth. However, the addition of aluminum to the beryllium-copper alloys is beneficial in that the tensile strengths of the cast, solution heat-treated and aged alloys are all greater then obtained with a binary alloy of the same beryllium content. It is believed that the aluminum distributes itself in the "beta-phase" and serves to enlarge the beta region of the beryllium-copper equilibrium diagram (see Frontispiece(4)).

It was found that iron, when added to the cast beryllium-copper alloys in amounts less than 0.75%, has a very beneficial effect,ie., refines the grain size and increases the tensile strength. The resultant grain refinement causes great improvement in elongation properties, particularly in the solution heat-treated alloys. In amounts greater than 0.75%, iron is detrimental in that the alloys are embrittled. The addition of iron, up to 2%, did not affect the ability of the alloy to develop full hardness. It is believed that the iron surpresses the beta region of the beryllium-copper diagram and that the iron is distributed in the "alpha-phase".

It is recommended that the aluminum content of the cast beryllium - copper alloys be kept as low as possible. The iron content of the cast beryllium-copper alloys may be allowed to increase up to 0.75%.

PART III

APPENDIX

PROCEDURE

A series of heats were calculated so as to give an analysis according to the scheme indicated below:

Be	Fe	Al	Si	Cu
2.25	0.04	0.10	0.08	Remainder
2.25	0.04	0.25	0.08	Remainder
2.25	0.04	0.50	0.08	Remainder
2.25	0.04	0.75	0.08	Remainder
2.25	0.04	1.00	0.08	Remainder
2.25	0.04	1.50	0.08	Remainder
2.25	0.04	2.00	0.08	Remainder
2.25	0.10	0.03	0.08	Remainder
2.25	0.25	0.03	0.08	Remainder
2.25	0.50	0.03	0.08	Remainder
2.25	0.75	0.03	0.08	Remainder
2.25	1.00	0.03	0.08	Remainder
2.25	1.50	0.03	0.08	Remainder
2.25	2.00	0.03	0.08	Remainder
2.25	0.04	0.03	0.08	Remainder

The materials used for melting the various heats were supplied by the Beryllium Corporation (master alloy containing 3.98% Be, 0.06% Fe, 0.13% Si, 0.05% Al, remainder Cu); Aluminum Company of America (ingot aluminum containing 99.9968% Al, 0.0011% Si, 0.0006% Fe, 0.0004% Cu, 0.0007% Mg, 0,0004% Na); American Brass Company (electrolytic copper punchings, analysis unknown); and Carnegie-Illinois Steel Company (S.A.E. 1010 steel containing 99.+% Fe, 0.15% C, 0.55% Mn, 0.016% P, 0.045% S.

Each of the heats was melted in a 12 lb, 30 K.W. high frequency induction furnace. The electrolytic copper punchings were melted first under a layer of coarse flake graphite and then the master alloy was added to the melt.

Immediately after the master alloy had dissolved, the aluminum addition was made without appreciably increasing the temperature. The temperature was then raised to 2300° F. for purposes of homogenization of the melt, cooled to 2100° F., the "graphite slag" skimmed off and the melt poured into molds when the temperature reached 2000° F.

The iron additions could not be made at as low a temperature as the aluminum additions so that the temperature of the molten punchings and master alloy was raised to 2850° F. and then the iron added. After making sure there was time for homogenization at 2850° F., the melt was cooled to 2400°F., the "graphite slag" skimmed off and the melt poured into molds when the temperature reached 2300° F.

The molds used were core sand molds made by mixing 100 parts lake sand, 7 parts cereal binder, 5 parts water and 3 parts oil binder. After "ramming up", the green core-sand half-molds were baked for 24 hours at approximately 500° F., cooled, and then the two halves of the mold were pasted together and baked for 8 hours at approximately 300° F.

The cast bars were allowed to cool and solidify to the extent of having solid metal in the pouring basin before the mold was broken open. The test bars were broken off the gates while the temperature was in the range 1300°F. to 1400° F. and cooled to room temperature in still air.

Each of the bars and heat was appropriately identified and the test bars removed to the machine shop for finishing. The machined bars conformed to the dimensions of the standard .505 in. test bar six inches long.

The finished bars were then ready for heat treatment. Two bars from each heat were solution heat-treated in an electric muffle furnace for a period of 72 hours at 1500° F. One bar of the solution heat treated alloys from each heat was then aged at 700° F. for a period of 2.5 hours in an electric muffle furnace.

Three bars (one cast, one solution heat-treated and one aged) from each heat were marked for elongation measurements and then broken in tension.

Elongation and maximum stress were recorded and percentage elongation and ultimate strength computed.

The non-gated end of the test bar, previously marked, was cut off, the flat surfaces machined parallel, and the penetration hardness determined using the appropriate scale, i.e., R_B or R_C.

The indentations from the hardness determinations were machined away and the surface polished for metallographic inspection. Each specimen was then etched with a solution consisting of 100 parts H_2O, 10 parts HCl and 5 parts $FeCl_3$, and examined under the microscope. Representative microstructures were chosen and typical photomicrographs were obtained at magnification of 100 diameters and 250 diameters.

ANALYSIS

The author is deeply indebted to Messrs. R. P. Nevers, E. M. Horton, and G. A. Reihl of the American Brass Company for the analyses of the various alloys(5).

The copper values were determined electrolytically on 2-gram samples. A 1-gram aliquot of exhausted electrolyte was used for beryllium and aluminum determinations and these separated by two precipitations with 8-hydroxyquinoline after removal of the iron in a mercury cathode cell. The method is one developed by the American Brass Company(6).

The iron was determined on the other 1-gram aliquot by titration with standard titanous chloride.

Silicon was determined photometrically in accordance with the method published by O. P. Cates of the American Brass Company(7).

Analysis No.	Sample Mark	Copper %	Beryllium %	Iron %	Aluminum %	Silicon %
76860	A	97.73	2.13	0.04	0.03	0.06
76861	B	97.63	2.25	0.04	0.03	0.07
76862	C	97.34	2.25	0.04	0.31	0.06
76863	D	97.12	2.26	0.04	0.60	0.06
76864	E	96.86	2.22	0.04	0.84	0.06
76865	F	96.69	2.18	0.04	1.07	0.07
76866	G	96.21	2.23	0.04	1.52	0.06
76867	H	95.60	2.26	0.04	2.09	0.06
76868	I	97.59	2.21	0.11	0.04	0.07
76869	J	97.56	2.18	0.24	0.03	0.07
76870	K	97.29	2.15	0.50	0.04	0.07
76871	L	96.94	2.21	0.75	0.03	0.07
76872	M	96.85	2.09	0.98	0.03	0.07
76873	N	96.27	2.12	1.40	0.03	0.08
76874	O	95.72	2.16	2.04	0.03	0.08

COLOR PHOTOMICROGRAPHY

The field of color photomicrography is relatively new and therefore only meager data is available to the metallographer. The field would probably be exploited very rapidly except for three factors; namely, the present exhorbitant cost of color film and color prints, the slow speed of the color emulsions, and lack of suitable exposure meters. The intensity of light obtained with color photomicrography is so low as to require the development of special photocells coupled with a suitable amplifying means in order that any accurate estimate of the exposure can be made. The added difficulty in handling and processing the film in anything but a color laboratory is another factor retarding the use of color photomicrography.

An attempt was made to incorporate the use of a 35 mm. camera in color photomicrography. This was accomplished by setting the camera lens for a subject distance of infinity and then setting the camera at the focal point of the ocular and perpendicular to the optical axis of the metallograph. The proper location of the camera accomplished through the use of an auxiliary stage.

The samples were properly polished and etched and then placed on the stage for examination and photographing. The samples were viewed at a number of magnifications and photographed experimentally so as to have a knowledge of the size of field produced by various combinations of objectives and oculars. The exposure timesused were 1 second, 2 seconds, and 4 seconds in accordance with the results of previous work by D. D. McGrady, J.R.Burnett, and the author.

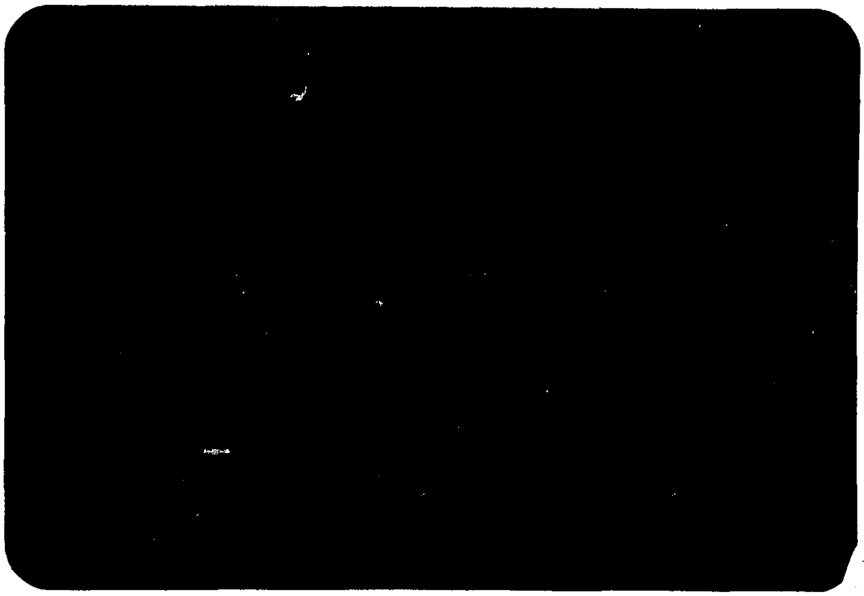

FIGURE 62. Microstructure of a cast alloy containing 2.25% Be- 97.63% Cu- 0.04% Fe- 0.03% Al- 0.07% Si.

Etch: Ferric Chloride
Objective: 5.6X
Ocular: 12.5X

Film: Kodachrome Type A
Exposure: 2 seconds
Filters: Wratten B and G

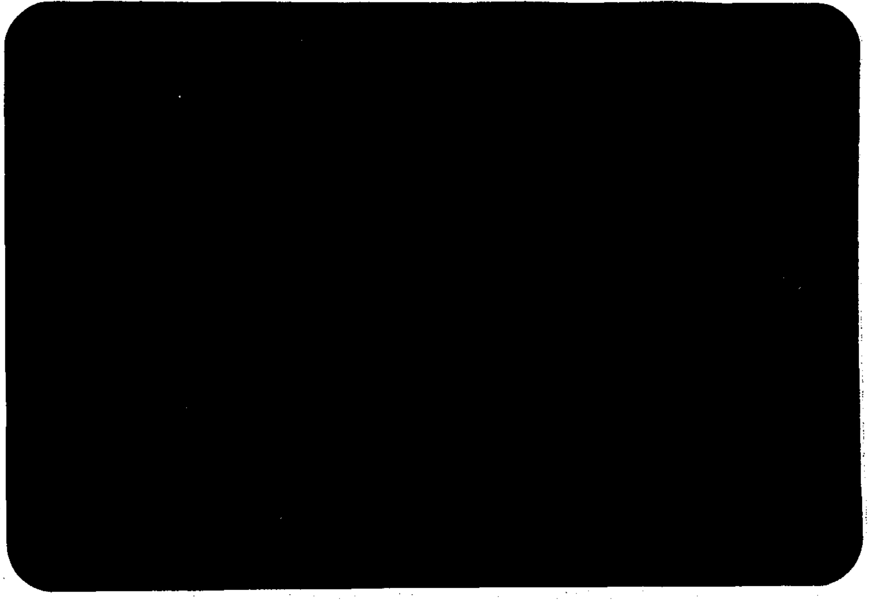

FIGURE 63. Microstructure of a cast, solution heat-treated and aged alloy containing 2.25% Be- 97.63% Cu- 0.04% Fe- 0.03% Al- 0.07% Si.

Etch: Ferric Chloride
Objective: 8X
Ocular: 12.5X

Film: Kodachrome Daylight
Exposure: 4 seconds
Filters: Wratten B and G

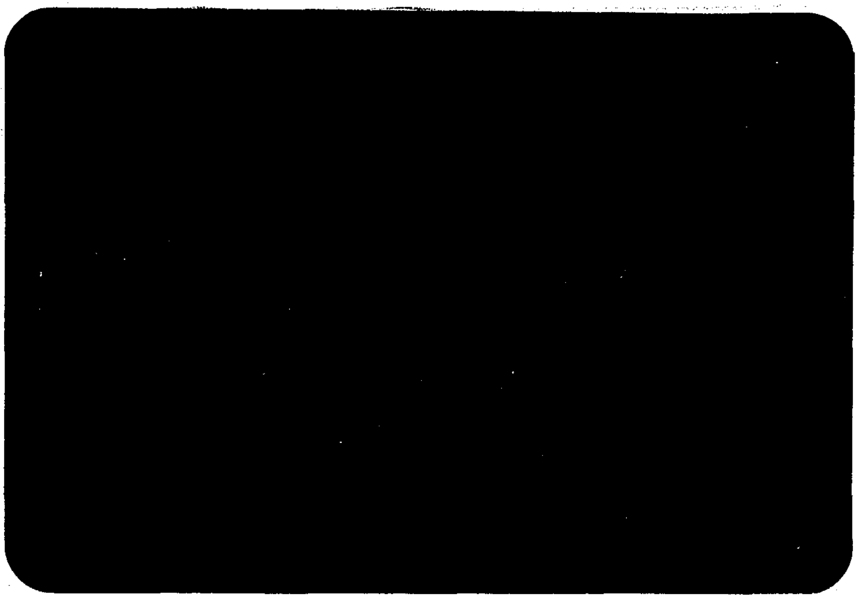

FIGURE 64. Microstructure of a cast alloy containing 2.26% Be- 95.60% Cu- 0.04% Fe- 2.09% Al- 0.06% Si.

Etch: Ferric Chloride
Objective: 8X
Ocular: 12.5X

Film: Kodachrome Daylight
Exposure: 4 seconds
Filters: Wratten B and G

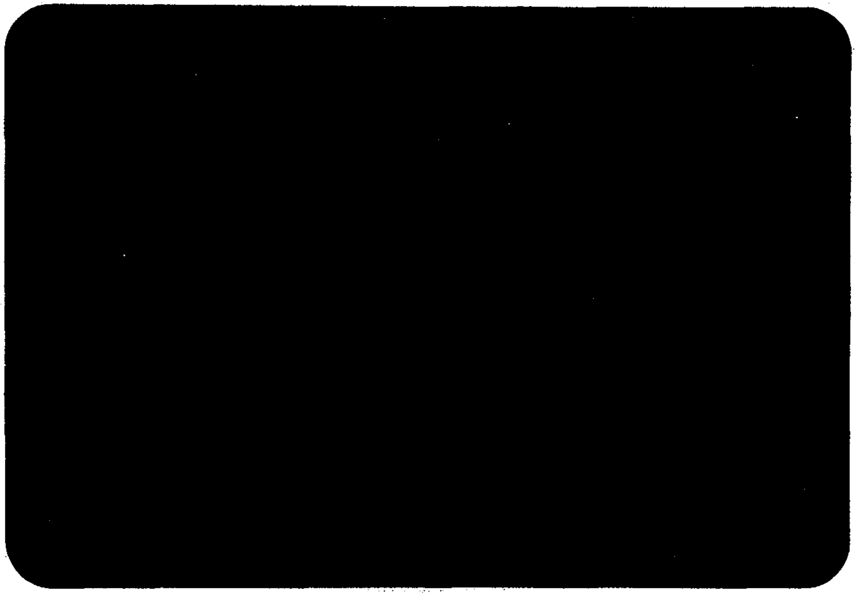

FIGURE 65. Microstructure of a cast alloy containing 2.16% Be- 95.72% Cu- 2.04% Fe- 0.03% Al- 0.08% Si.

Etch: Ferric Chloride
Objective: 21X
Ocular: 12.5X

Film: Kodachrome Daylight
Exposure: 4 seconds
Filters: Wratten B and G

The results of this experimental work indicated that the field of the 35 mm. film is adequately filled when the following objective-ocular combinations are used:

Objective	Ocular
5.6X	15X or higher power
8X	12.5X or higher power
21X	12.5X or higher power
41X	12.5X or higher power

Experimentation was carried out as regards the type of color film, i.e., Kodachrome type A and Kodachrome Daylight type. It was found that the type of color film did not influence the results under the following conditions: tungsten filament illumination incident normally to surface, quarter-wave plate inserted with and without auxiliary green and/or yellow filters.

Figures 62 through 65 are typical photomicrographs of some of the beryllium-copper alloys utilized in the fore-part of this investigation.

The equipment used for this portion of the investigation consisted of a Bausch and Lomb Research Metallograph, a series of Wratten filters, and a Kodak 35 mm. camera with a coated lens.

Inspection of the transparencies shows that the color reproduction is not exact. However, there is still considerable value in color photomicrography even though color reproduction is not exact. The various phase are so vividly differentiated that the exactness of color reproduction is of little consequence in the analysis of a microstructure.

The Kodachrome prints exhibited herein are very poor reproductions of the transparencies at best.

It is found by experience that transparencies that are to be made into prints must necessarily be on the "thin" side. Those transparencies intended for projection are best when the transparency has been underexposed.

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