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C. J. Adams

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THE ALLOYS OF GALLIUM AND INDIUM

By

C. J. Adams

A Thesis
Submitted to the Department of Metallurgy
in Partial Fulfillment of the
Requirements for the Degree of
Bachelor of Science in Metallurgical Engineering

Montana School of Mines
Butte, Montana
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The experimental work for this thesis was carried out in association with Allen D. Kennedy, a Senior in Metallurgical Engineering at Montana School of Mines.

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THE ALLOYS OF GALLIUM AND INDIUM

INTRODUCTION

This problem was undertaken for the purpose of constructing the gallium-indium equilibrium diagram, to investigate the alloys of gallium and indium, and to recover the pure metals from their alloys. Recovery of gallium was especially important because of the scarcity and the high price of the metal -- three to six times as expensive as gold.(7^b)

Thermal analysis was used to construct cooling and heating curves from which the phase diagram was determined. The data for the entire set of cooling curves were obtained by the use of mercury thermometers.

The alloys were prepared for subsequent microscopic examination and photomicrography, after the heating and cooling curves were determined.

The gallium-indium equilibrium diagram is one that shows complete solubility in the liquid state and complete insolubility in the solid state -- the eutectic reaction.

THEORETICAL DISCUSSION

BINARY EQUILIBRIUM DIAGRAMS

The equilibrium diagram is a composite picture, which is used to predict what the normal internal structure of an alloy will be in advance of its preparation. Both physical and chemical properties of an alloy can be predicted when the structure is known. From the diagram it is possible to predict the amount of eutectic or peritectic that the alloy will possess after solidification, the amount of primary crystals, the temperature of initial freezing, the composition of each phase, and the temperature of complete solidification.(3)

"The equilibrium diagram for binary alloy systems is a temperature-composition plot in two dimensions; the lines on this diagram are the loci of all the critical points of all the alloys in the system. The various lines on a binary equilibrium system divide it into a number of closed fields or regions; these must be either one-phase or two-phase fields."(6a)

THE EUTECTIC REACTION(2,3)

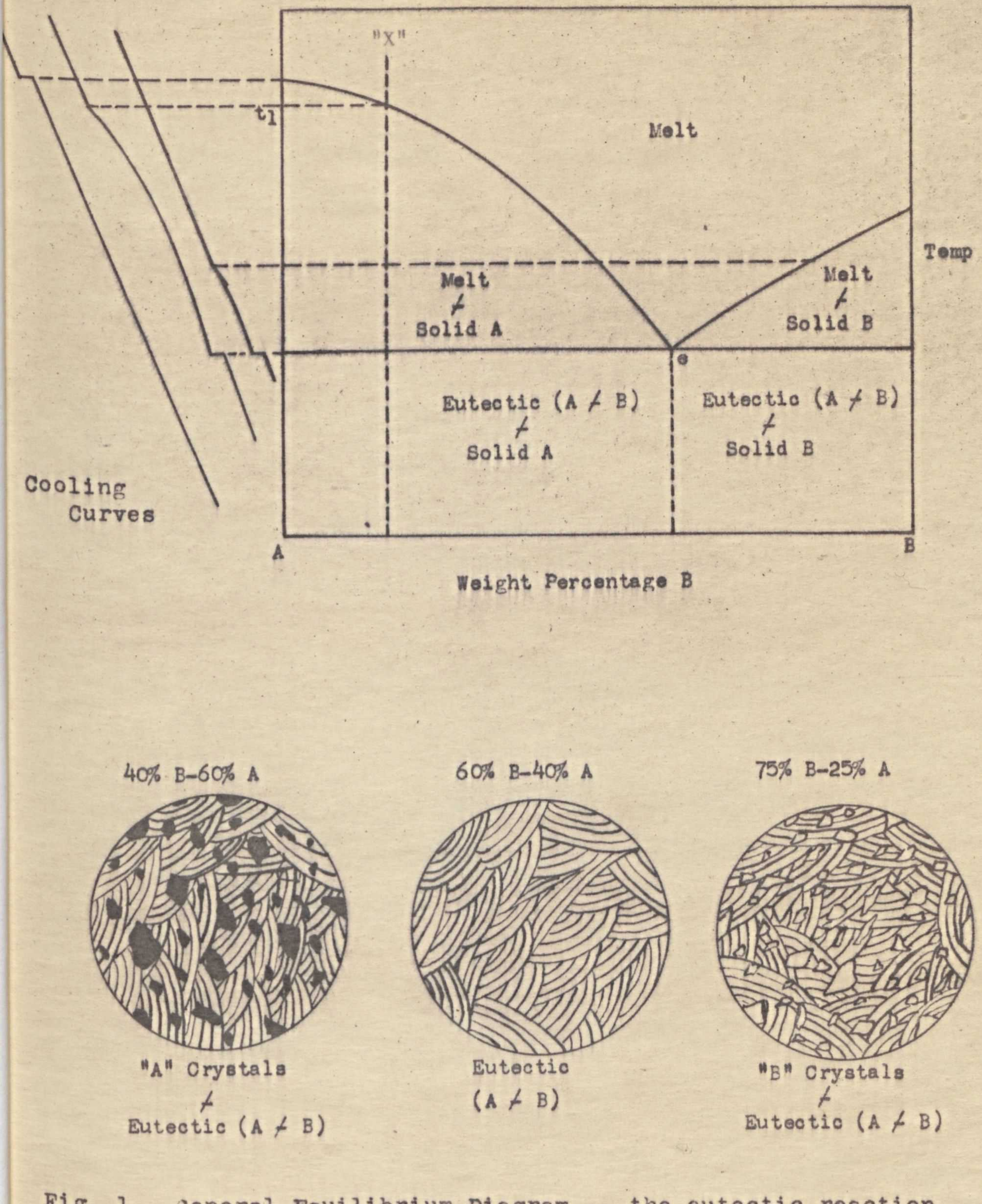
The binary equilibrium diagram determined in this investigation represents those diagrams of complete liquid solubility and complete solid insolubility or the eutectic reaction. Theoretically there is no such thing as complete insolubility. Either the solubility is so slight that it cannot be shown on a diagram or the system has not been investigated in sufficient detail.

Raoult's law states that the freezing point of a pure substance will be lowered by the addition of a second substance (provided that the latter is soluble in the pure substance while liquid and insoluble in it while solidified), the amount of lowering being proportional to the molecular weight of the solute.

Fig. 1 illustrates the method used in reading the equilibrium diagram.

The abscissa represents the variation in composition of the alloy. The ordinates represent the variation of temperature. The extreme left ordinate represents the freezing point of the pure element A, and the extreme right ordinate represents the freezing point of the pure element B.

Above the liquidus line there is only one phase -- the liquid state. The region below the liquidus is a two-phase field containing one liquid and one crystalline phase. The liquidus indicates the temperature at which freezing begins for each alloy. At the eutectic temperature there are three phases (liquid, crystals A, and crystals B).



"A" Crystals + Eutectic (A + B)

Eutectic (A + B)

"B" Crystals + Eutectic (A + B)

Fig. 1. General Equilibrium Diagram -- the eutectic reaction.

The region below the solidus is a two-phase field containing two crystalline phases.

An alloy "X" will be selected to illustrate the cooling of an alloy (Fig. 1). Where the alloy X cuts the liquidus, the crystalline phase has a composition of 100 per cent A. At the temperature t_1 pure A crystals will begin to precipitate, which will leave the liquid richer in B. No further precipitation of A crystals will take place until the temperature has been lowered. As the temperature continues to drop, the amount of crystalline phase will gradually increase by the continued precipitation of A crystals from the melt, and the liquid phase gradually decrease in amount, constantly becoming richer in B. At point "e" the liquid is saturated with both A and B crystals. At this point, the crystals of A and B will precipitate alternately at various points in the remaining liquid until solidification is complete. The temperature and composition of all three phases -- melt, A crystals, and B crystals -- does not change during the process. The dissociation of the eutectic liquid is known as the eutectic reaction.(2a)

$$\text{Liquid "e"} \underset{\text{Heating}}{\overset{\text{Cooling}}{\rightleftharpoons}} \text{crystals A} + \text{crystals B}$$

Since solidification for all alloys is completed at this temperature, a horizontal line may be drawn across the entire diagram -- the solidus line.

THERMAL ANALYSIS(4,6)

Thermal analysis is a method of observing phase changes by the study of cooling curves. Most of the solubility limits of the possible binary phase diagrams havebeen obtained by the method of thermal analysis, but there is a limit to the use of thermal analysis to produce phase diagrams. The purpose of thermal analysis is to determine the exact temperature at which transformation takes place. When the temperature of a cooling body is plotted against the time, a cooling curve is obtained. The temperature is a continuous function of time. The curve is continuous as long as no physical transformation or allotropic changes within the metal occur.

When heating at constant pressure, transformation from solid to liquid is accompanied by an absorption of heat, and upon cooling at constant pressure, transformation is accompanied by an evolution of heat. The heat of fusion evolved in cooling counteracts the cooling loss so that the temperature remains constant for a given time until the phase change is complete. At this point there is a job or inflection in the curve which is called a critical point. After the change is complete, cooling continues, and a smooth curve is obtained again. Supercooling or surfusion will cause the curve to dip just before the freezing points are reached.

A heating curve is similar to a cooling curve except that observations are made as the metal is being heated. Because of the hysteresis of the material, the critical points will be slightly different from those obtained by cooling curves.

Certain pure metals and alloys undergo allotropic transformations in the solid state. These solid-state transformations are accompanied by heat changes and are not always detectable by thermal analysis.

If the heat effects are relatively small and they do not alter the curves sufficiently, other methods of detection may have to be employed.

COOLING CURVES(4)

If the heat effects at the transition points are too small to be detectable by the direct time-temperature cooling curves, other methods of plotting curves may be used (Fig. 2a).

The inverse-rate cooling curve consists of plotting the absolute time interval required for a definite and arbitrary temperature change against the temperature. The time must be accurately measured for these curves (Fig. 2b).

Minor transformation points may be detected by the differential method. This method consists of plotting the temperature of a given specimen against the temperature difference between the specimen and a neutral body. The neutral body is a metal that does not undergo transformation. The temperature difference will be small except at the transformation points. At these points there is no interruption in the temperature of the neutral body, whereas there is a drop in temperature of the specimen under investigation (Fig. 2c).

In the derived differential method, the differential curve is differentiated with respect to the temperature. These values are plotted against the temperature. The only difference in this method from the differential method is in plotting the data. Transformation points by this method are more apparent than by the differential method (Fig. 2d).

SUPERCOOLING(4a, 7a)

When the liquid and solid states do not attain equilibrium after being cooled to the true freezing point, supercooling or surfusion results. The solution remains liquid when cooled below the true freezing point and is considered to be in a metastable state. Once freezing does begin, the temperature will rise very rapidly, as the heat evolved during the reaction is greater than that conducted away. The temperature will rise to the true freezing point and level off, and cooling continues in the normal way. The temperature may not rise to the true freezing point if more than one phase is present -- one phase that supercools and one phase that does

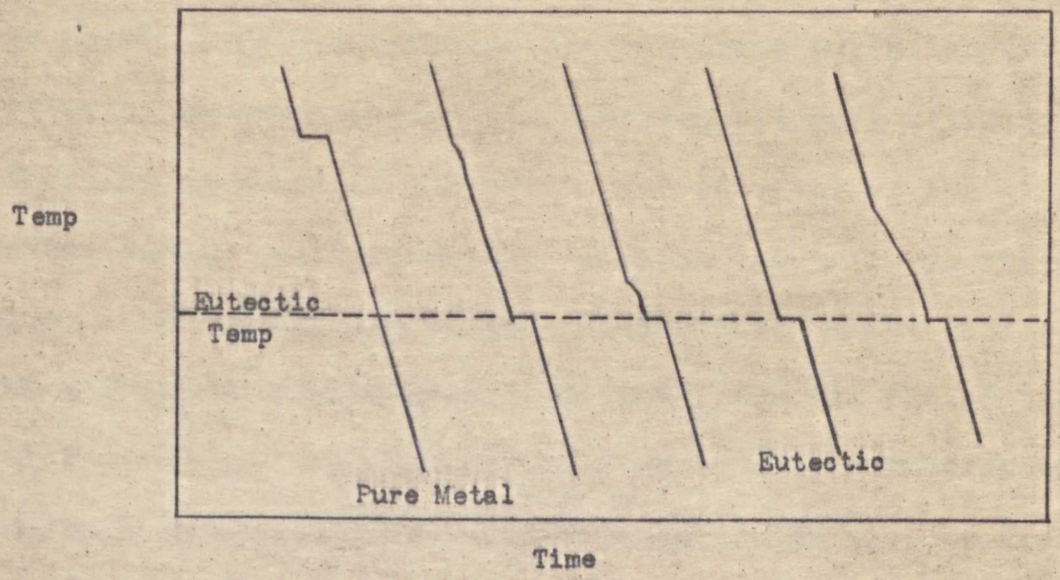


Fig. 2a. Time-temperature cooling curves for a eutectic reaction.

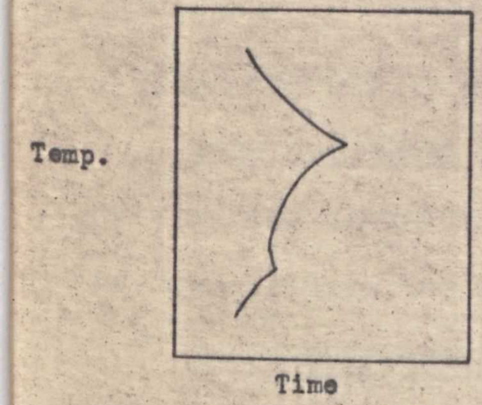


Fig. 2b. Inverse-rate cooling curve.

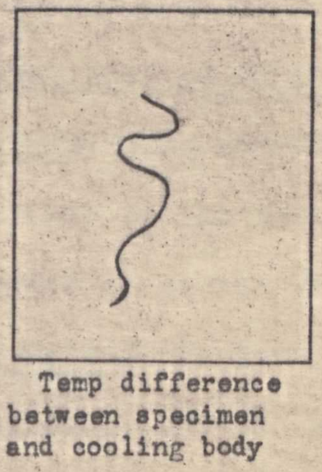


Fig. 2c. Differential cooling curve.

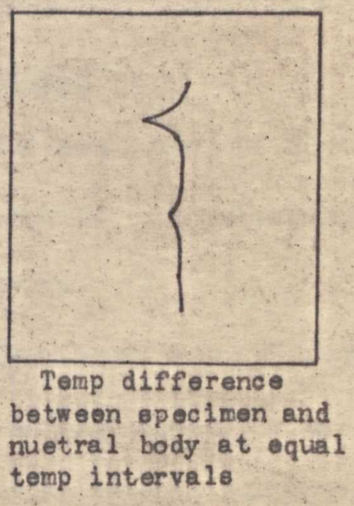


Fig. 2d. Derived differential cooling curve.

not supercool. The amount of supercooling can be controlled to some extent. Any condition that maximizes the formation of nucleation points in the melt will minimize supercooling in metals. Some conditions that minimize surfusion are low rates of cooling, heating to temperatures only slightly above the melting point of the metal, and stirring of the liquid metal during solidification. At high temperatures there are only a relatively few centers ofnucleation which will serve as nucleation points during freezing, and the faster the rate of cooling the less chance there is for the formation of these nucleation points. The amount of surfusion will be greater when heated to high temperatures and cooled rapidly than when heated just slightly above the melting point and cooled slowly. Stirring of the metal during solidification probably makes these points of nucleation more effective.

OTHER METHODS OF DETERMINING PHASE DIAGRAMS(4,5)

Metallographic Method: This method is best suited for determining transformations in the solid state and especially for determining the number of phases present.

X-ray Diffraction Method: Probably the best method for determining phase transformations in the solid state is by X-rays. This method is one of the recently adapted methods used in determining phase diagrams.

Dilatometry: The expansion or contraction caused in a metal by changes in temperature or structure can be detected with a dilatometer. This method is applicable only when determining solid-state transformations.

Other methods of determining transformations in the solid state are the electrical-resistivity method and the magnetic method.

PROPERTIES OF GALLIUM(1,7)

Gallium was discovered in 1874 by Boisbaudran by spectroscopic analysis. The name, gallium, was chosen in honor of Boisbaudran's native country -- Gallia is the Latin name for France.

Gallium, one of the rarest elements, is rated 47th in abundance in the earth's crust. It is distributed very widely, but in small quantities. The waste muds from electrolytic refining of various metals, especially zinc, and the flue dust from volatile metals contain gallium.

Table I. Physical Properties

Atomic number	31
Atomic weight	69.72
Atomic refraction	14.8
Boiling point	1600-2400°C
Color	grayish
Electrical Resistivity	$53.4 \cdot 10^{-6}$ ohm-cm
Isotopes	69, 71
Melting point	29.75°C
Specific gravity -- solid	5.91
-- liquid	6.08
Specific	0.079
Crystal system	tetragonal
Valence	3,2

The outstanding or peculiar properties of gallium are its tendency to supercool, the large difference between the melting point and boiling point, its expansion of freezing, its wetting behavior, and its corrosive properties.

"Qualitative tests established that a 76 per cent gallium -- 24 per cent indium alloy wets many substances, including glazed porcelain, quartz, glass, nickel, carbon, Plexiglas, ferric stearate, and Alundum. Little or no wetting occurred on paraffin, lead foil, or paper. It was eventually established that melting could be conducted in a Pyrex tube, under a cover of distilled water or paraffin, without wetting of the glass."(7b)

"The corrosive property of gallium was strikingly brought to the attention of the investigators when, in weighing a small pellet of gallium, it melted on the laboratory balance pan. Although the melt was removed immediately, the pan was found to be severely pitted."(7)

Another interesting property of gallium is that when a number of small globules of gallium or a thin film of gallium is brought near hydrochloric acid, the gallium will contract into a spherical mass.

Pure gallium will preserve its luster in air and in boiling air-free water, but will form an oxide coating in boiling water which contains dissolved air.

At present the commercial applications of gallium are few. Gallium has been used in high-temperature thermometers, metallic vapor lamps, optical mirrors, and dental amalgams.

"Recent quotations run from $2.50 to $7.50 per gram, making gallium three to six times as expensive as gold."(7)

PROPERTIES OF INDIUM(1)

Indium was also discovered by the spectroscope in 1863 by Reich and Richter. It was named after the color of its spectral lines.

Table II. Physical Properties

Atomic number	49
Atomic weight	114.76
Brinnel hardness	1
Boiling point	greater than 1450°C
Color	silvery-white
Crystal system	tetragonal
Isotopes.	115,113
Melting point	155.6°C
Resistivity (20°C)	$9 \cdot 10^{-6}$ ohm-cm
Specific gravity.	0.057 cal/g
Tensile strength.	15,980 lb/sq in
Valences.	3,2,1

Indium, like tin, emits a "cry" when bent. It is softer than lead and may be drawn into a wire. At ordinary temperatures, pure indium metal is not oxidized.

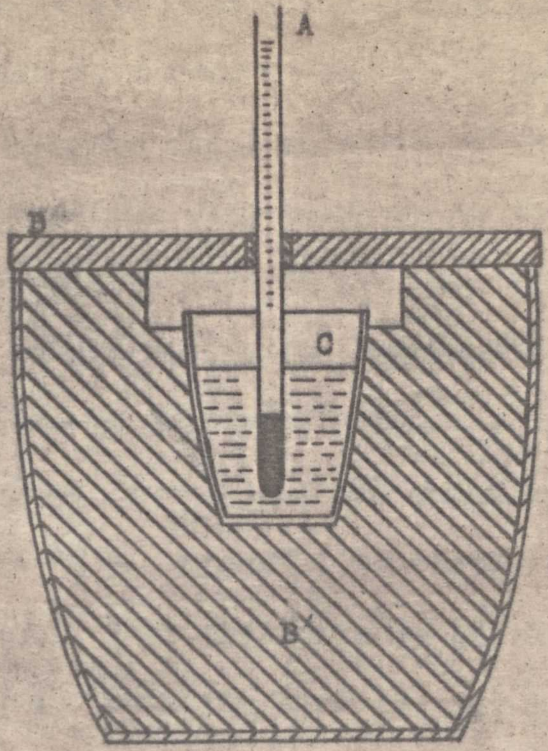
Indium diffuses very readily by low-temperature heat treatment. This diffusion may be considered as an actual alloying with the base metal. Plating another metal with indium greatly increases the corrosion resistance of the metal and increases the resistance to chipping or peeling.(1a)

Indium is used in silver-indium-lead bearing alloys for high-power aircraft engines and in bearing alloys for internal combustion engines. It is also used in dental alloys. The tarnish resistance and high reflectivity make indium useful in the field of optics. Indium oxide can be used to color glass from light to dark yellow.

EXPERIMENTAL WORK

Electrolytically pure gallium and indium were used to prepare the alloys. A small glazed-porcelain crucible, of about 80 grams capacity, was used for the preparation of the alloys. The porcelain crucible was imbedded in a larger clay crucible, which was fitted with an asbestos cover (Fig. 3). A Bunsen burner was used to heat the alloys -- hot water was used to heat the low-melting alloys. Air cooling was used until the critical point on the liquidus was passed, and then the clay crucible was transferred to a bath of ice and salt. The salt was necessary to lower the temperature below zero degrees Centigrade. Below zero degrees Centigrade, the glazed-porcelain crucible was transferred directly to the ice-salt bath.

The data for the heating and cooling curves were obtained by the use of mercury thermometers, which were calibrated to



A. Thermometer
B. Clay crucible
C. Porcelain crucible containing the alloys
D. Asbestos cover

Fig. 3. Cross section of design of equipment used for thermal analysis.

read to the closest 0.2°C. Estimations to 0.1° were made.

About 30 grams of liquid gallium were added to a weighed-porcelain crucible, and the crucible and contents were then weighed again to determine the exact amount of gallium. Solid indium metal was then added to the liquid gallium metal to bring the weight percentage up to the desired point. That part of the diagram from 50 per cent indium to 100 per cent indium was determined first. After the heating and cooling curves for the 50 per cent indium - 50 per cent gallium alloy were determined, additional solid indium metal was added to the crucible to bring the alloy composition up to the next desired point. When the contents of the crucible became too large to be conveniently handled, the sample was cut and calculations were adjusted. The other half of the diagram was determined from heating and cooling curves starting with 100 per cent gallium, and solid indium was added in the manner previously described. Heating and cooling curves were made for alloys containing 1, 3, 5, 10, 15, 20, 22, 24, 27, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, and 98 per cent indium. Data for the cooling and heating curves are given in the appendix and the curves are shown in Fig. 4 to Fig. 14. The equilibrium diagram constructed from the critical points obtained from the heating and cooling curves is shown in Fig. 15. Atomic percentages were calculated by the use of the following formula:

50% Ga-50% In Alloy

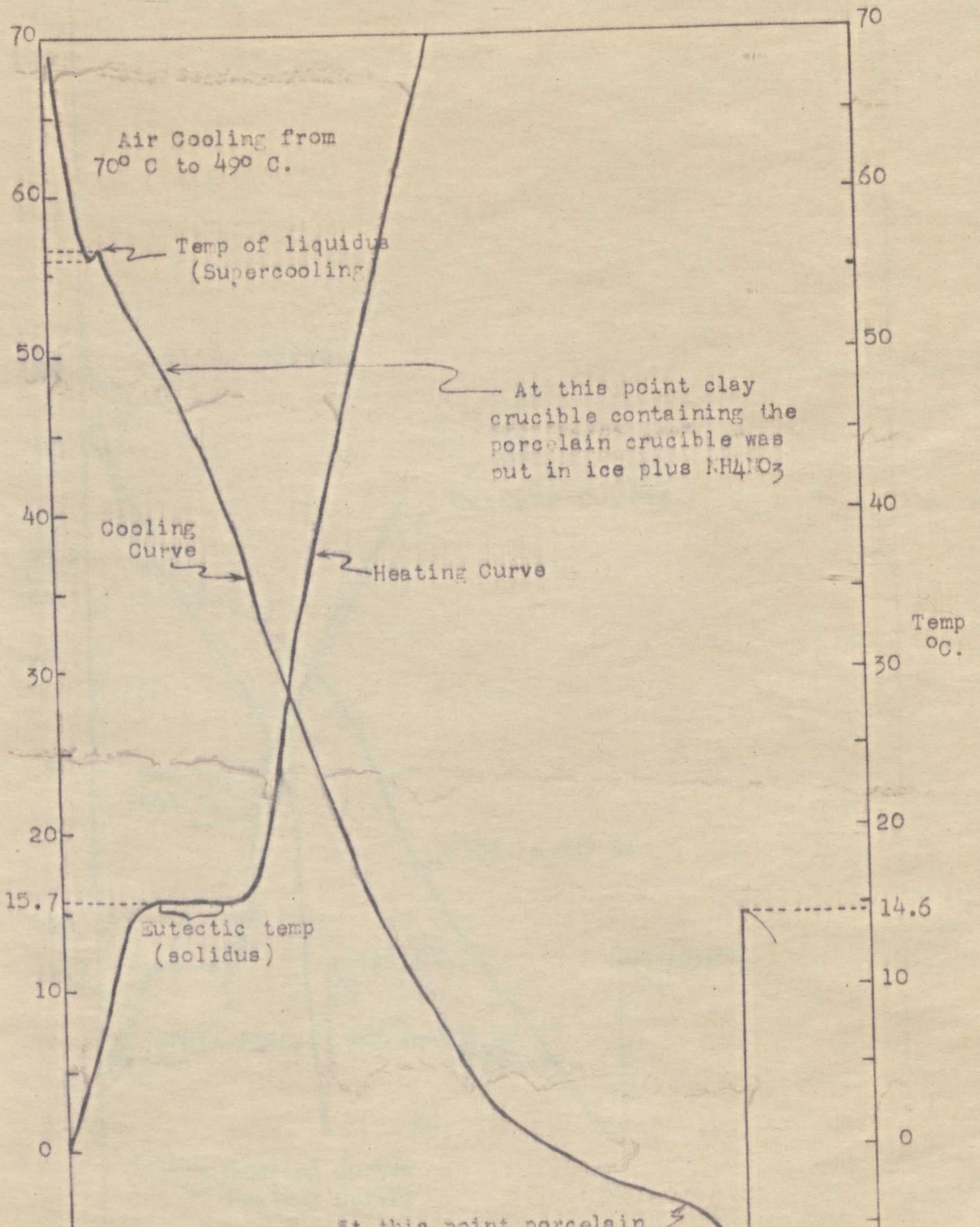


Fig. 4. Ga-In Heating and Cooling Curves

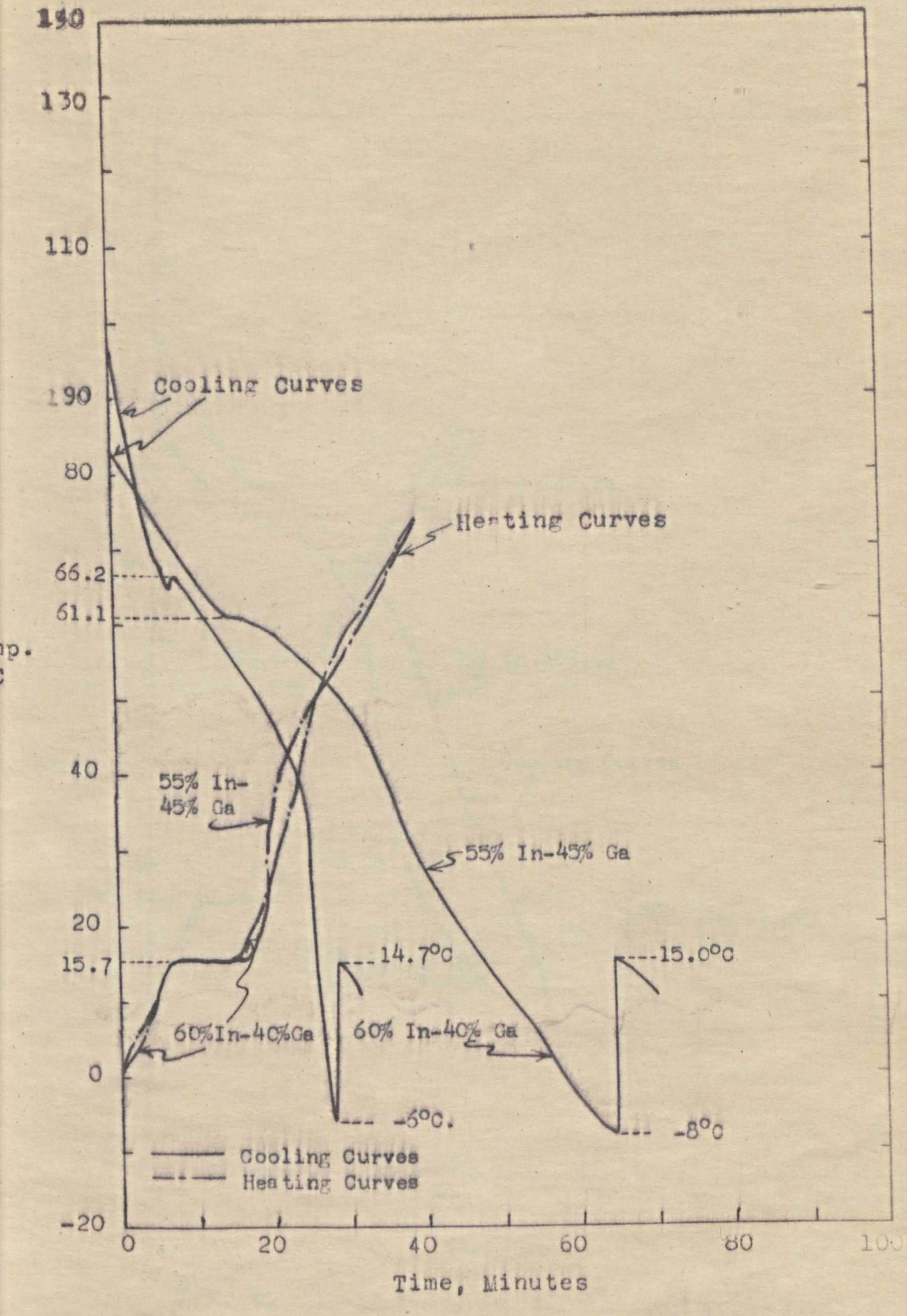


Fig. 5. Ga-In Heating and Cooling Curves

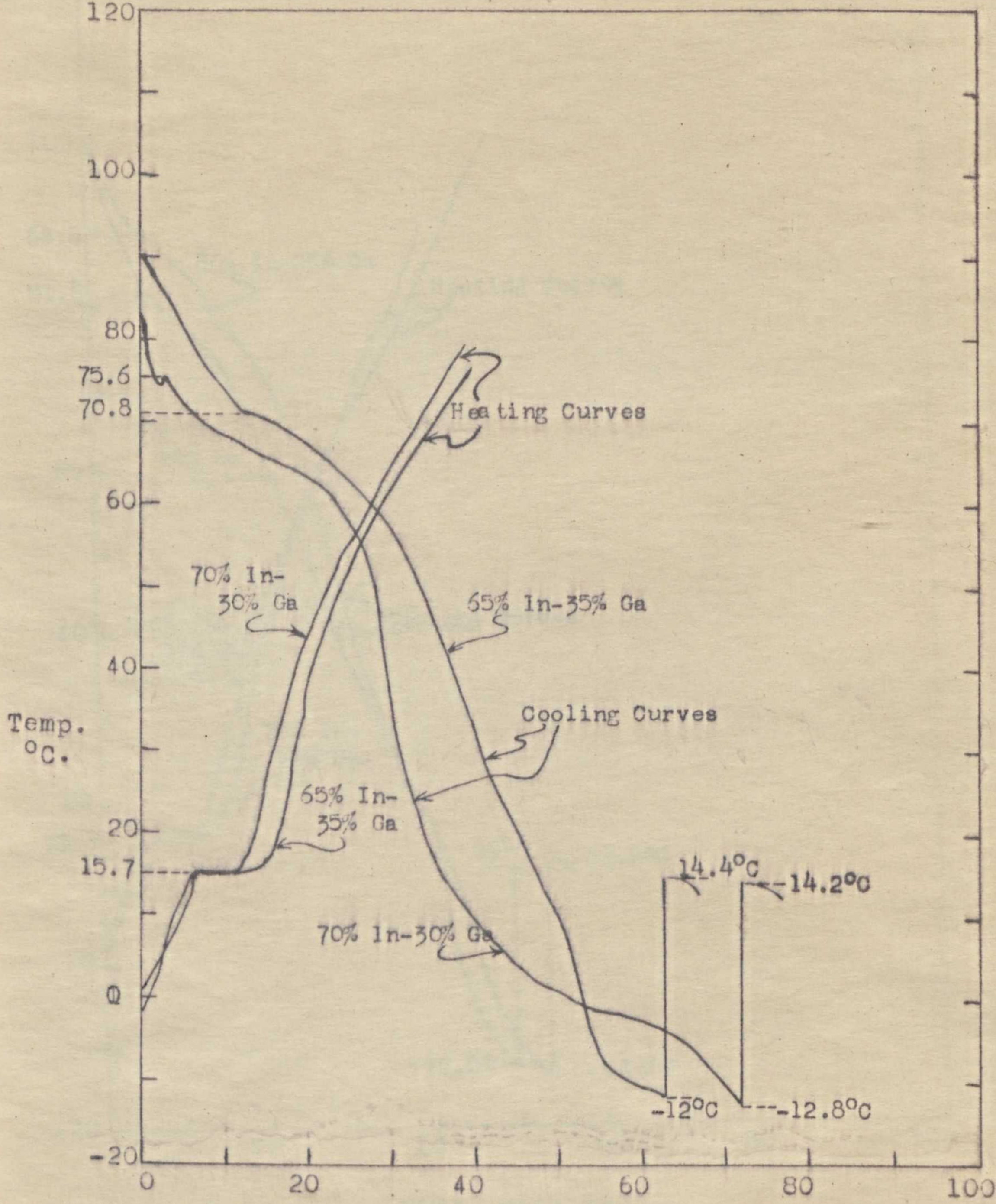


Fig. 6. Ga-In Heating and Cooling Curves.

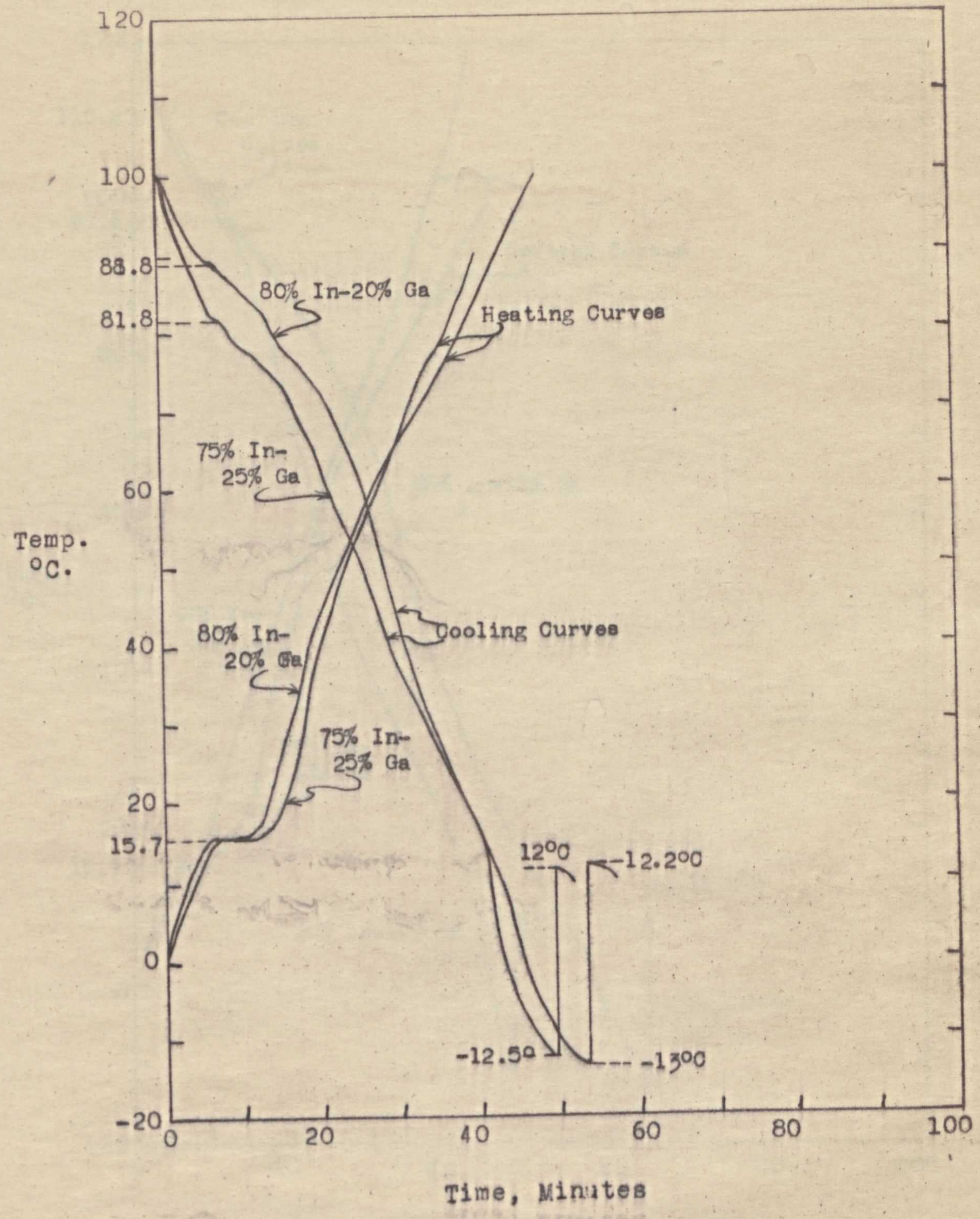


Fig. 7. Ga-In Cooling and Heating Curves

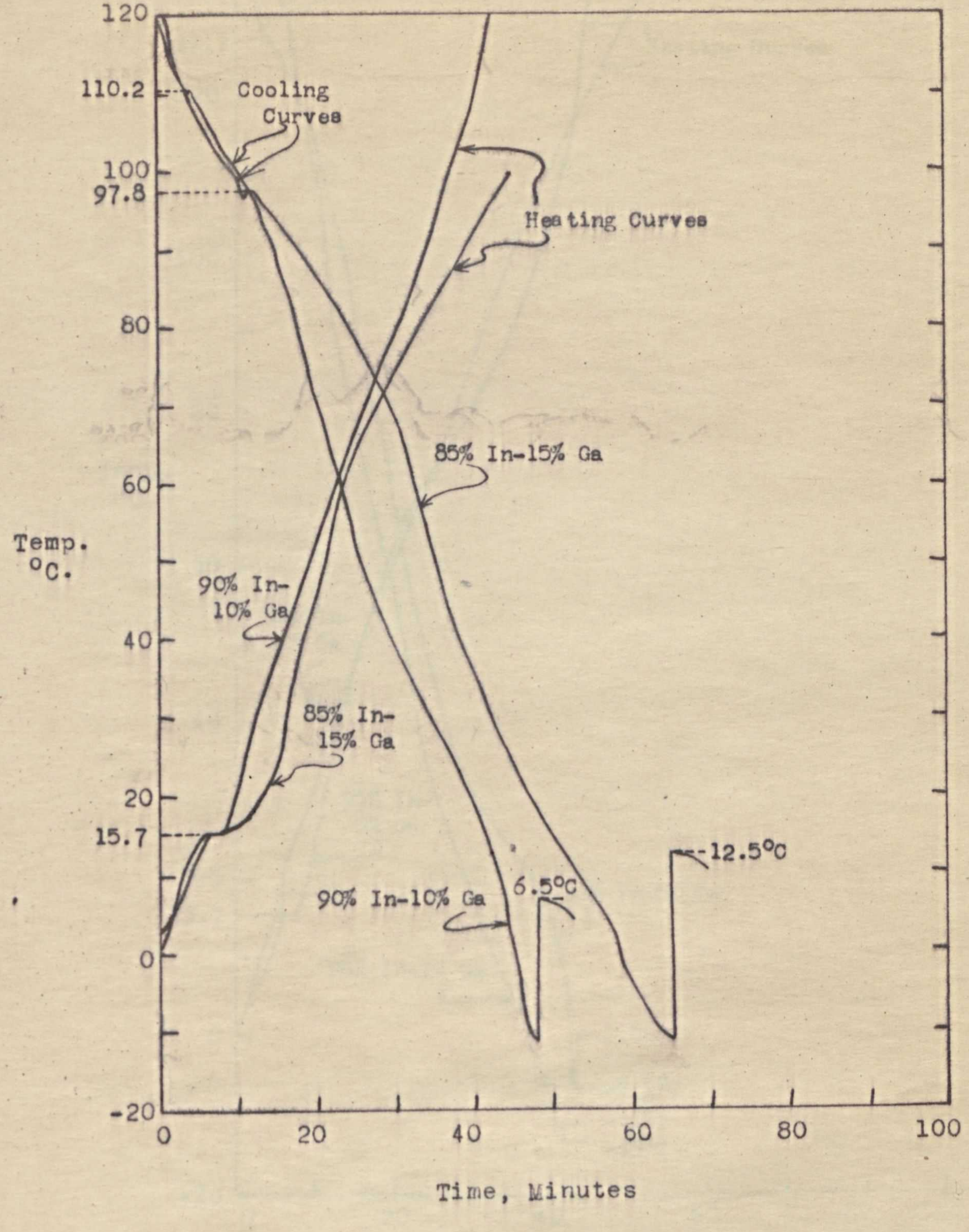


Fig. 8. Ga-In Cooling and Heating Curves

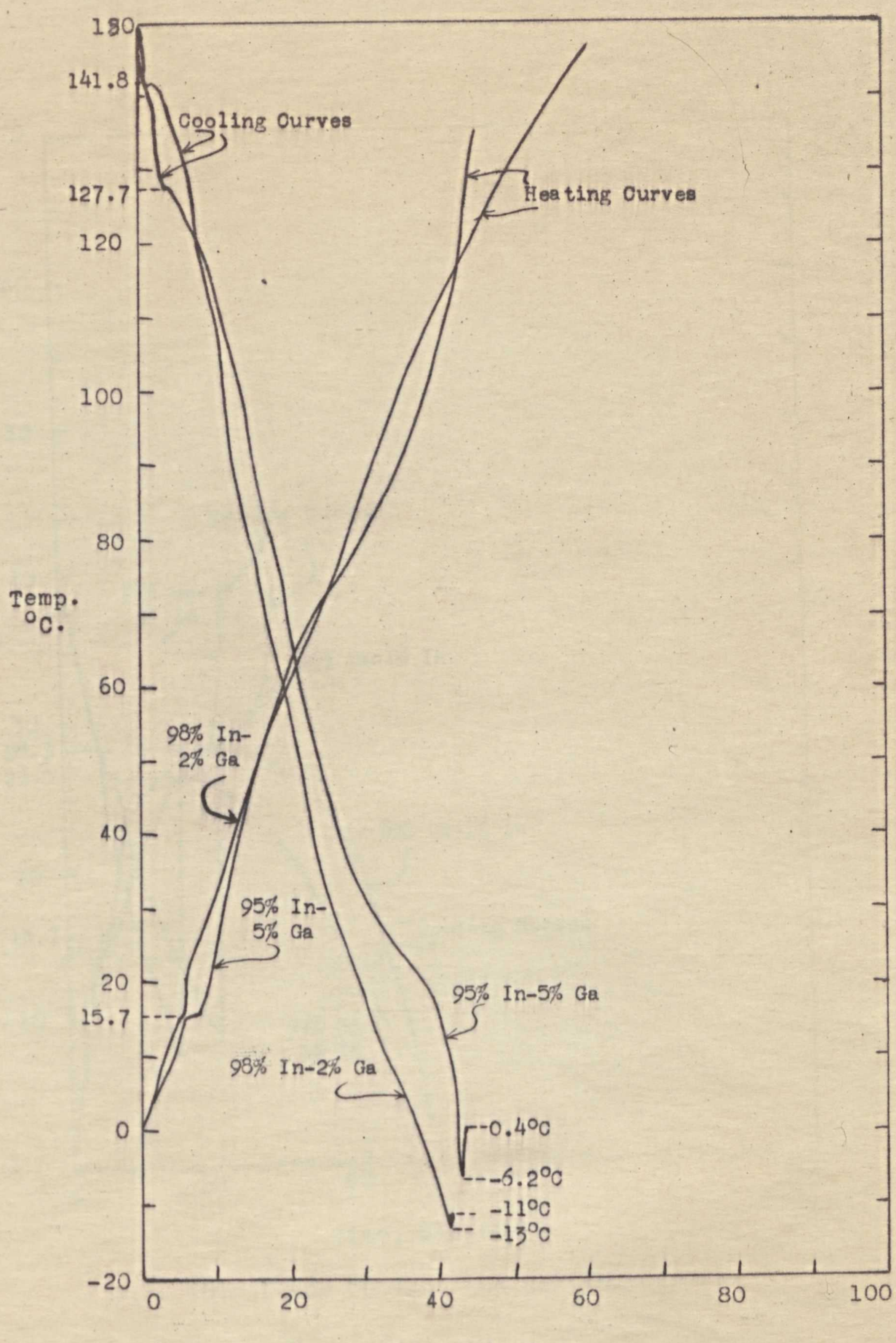


Fig. 9. Ga-In Cooling and Heating Curves

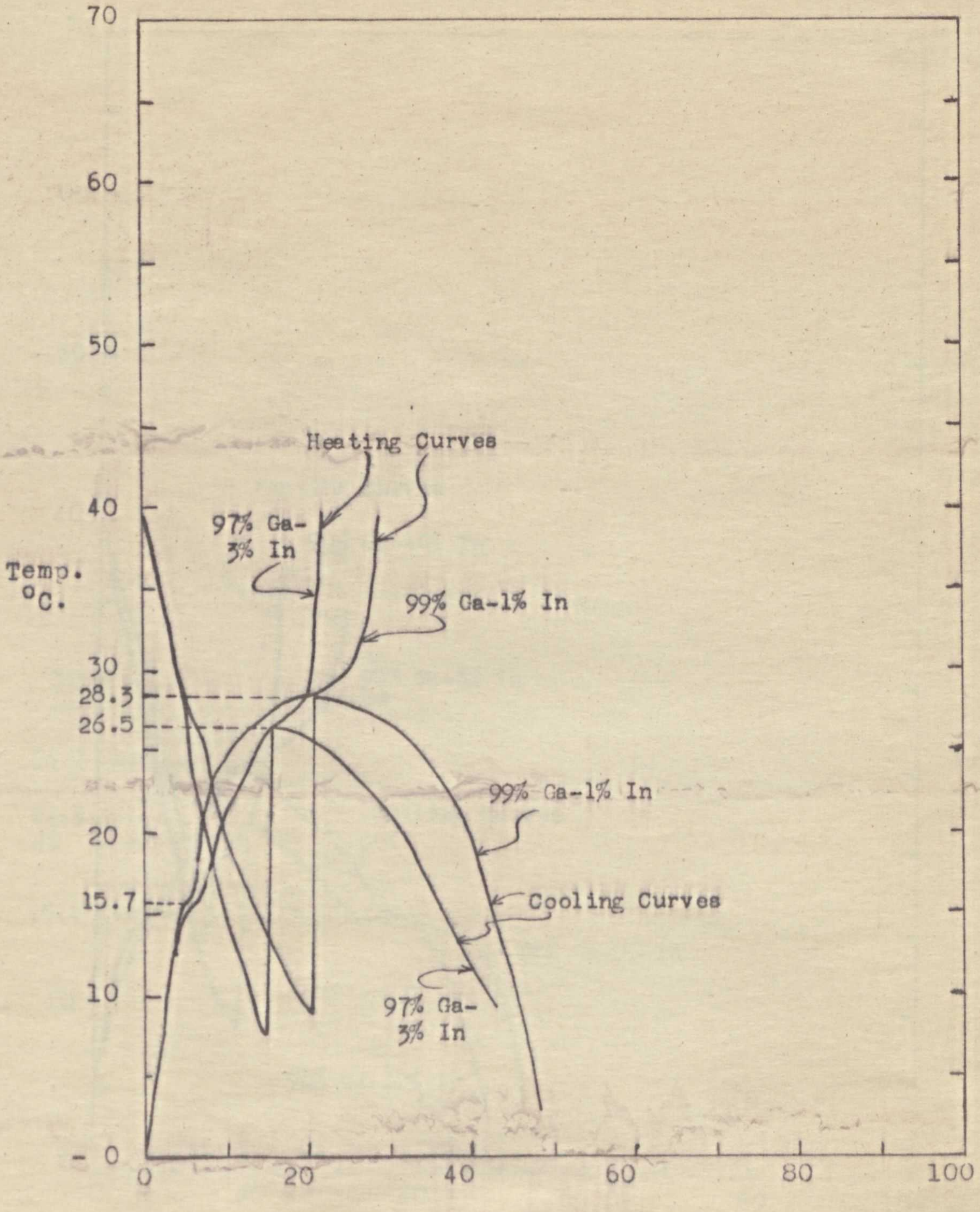


Fig. 10. In-Ga Cooling and Heating Curves.

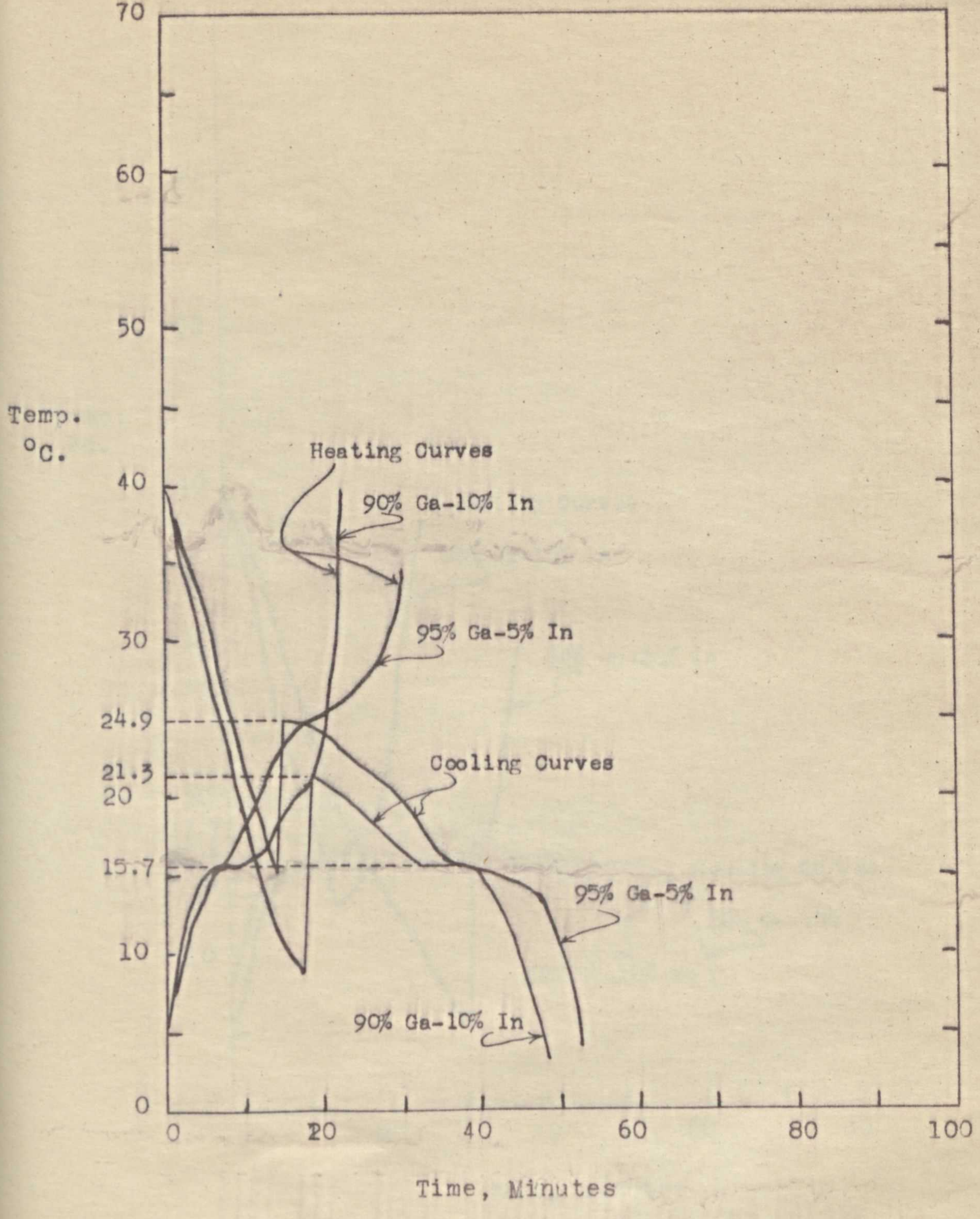


Fig. 11. In-Ga Cooling and Heating Curves.

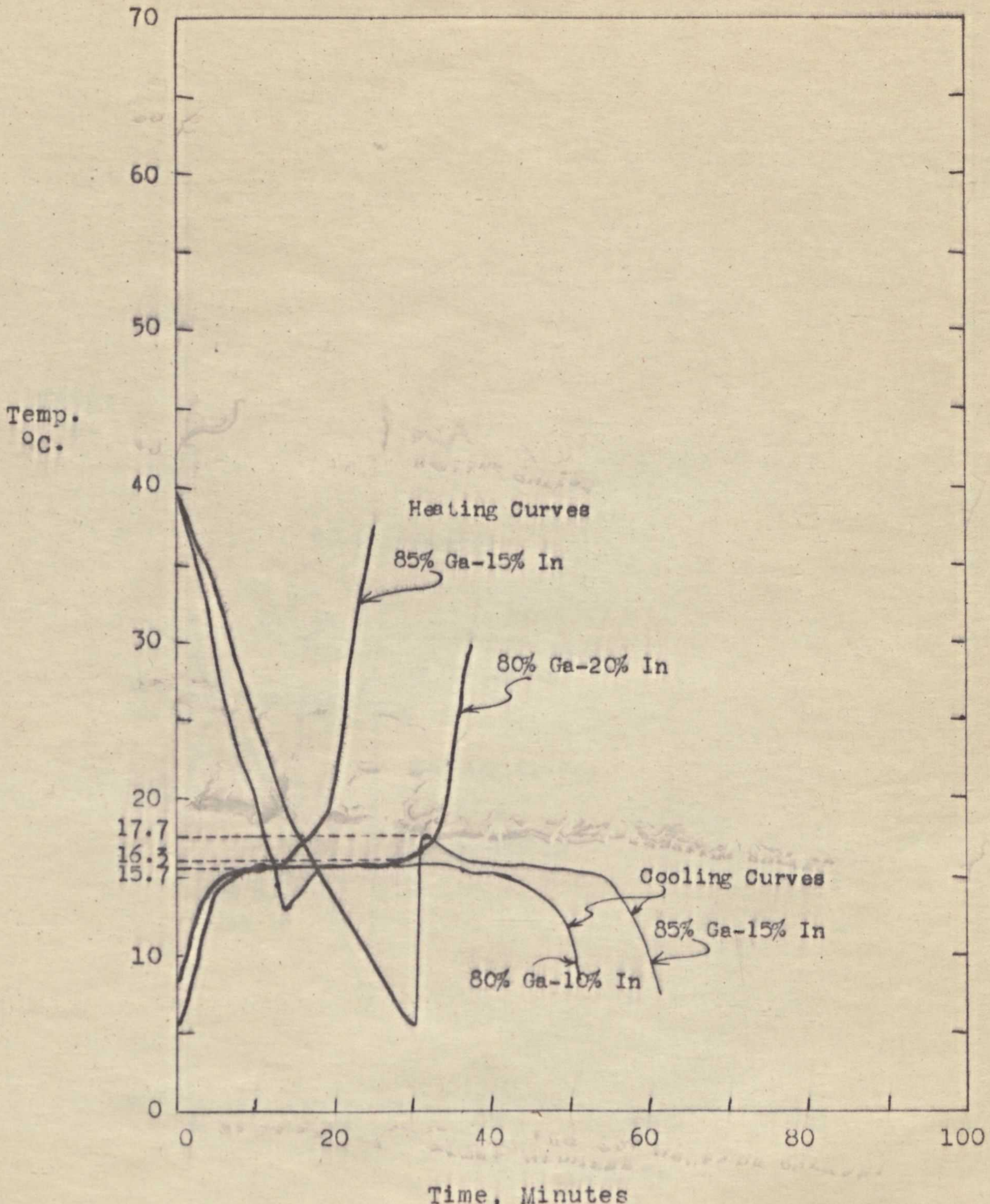


Fig. 12. In-Ga Cooling and Heating Curves.

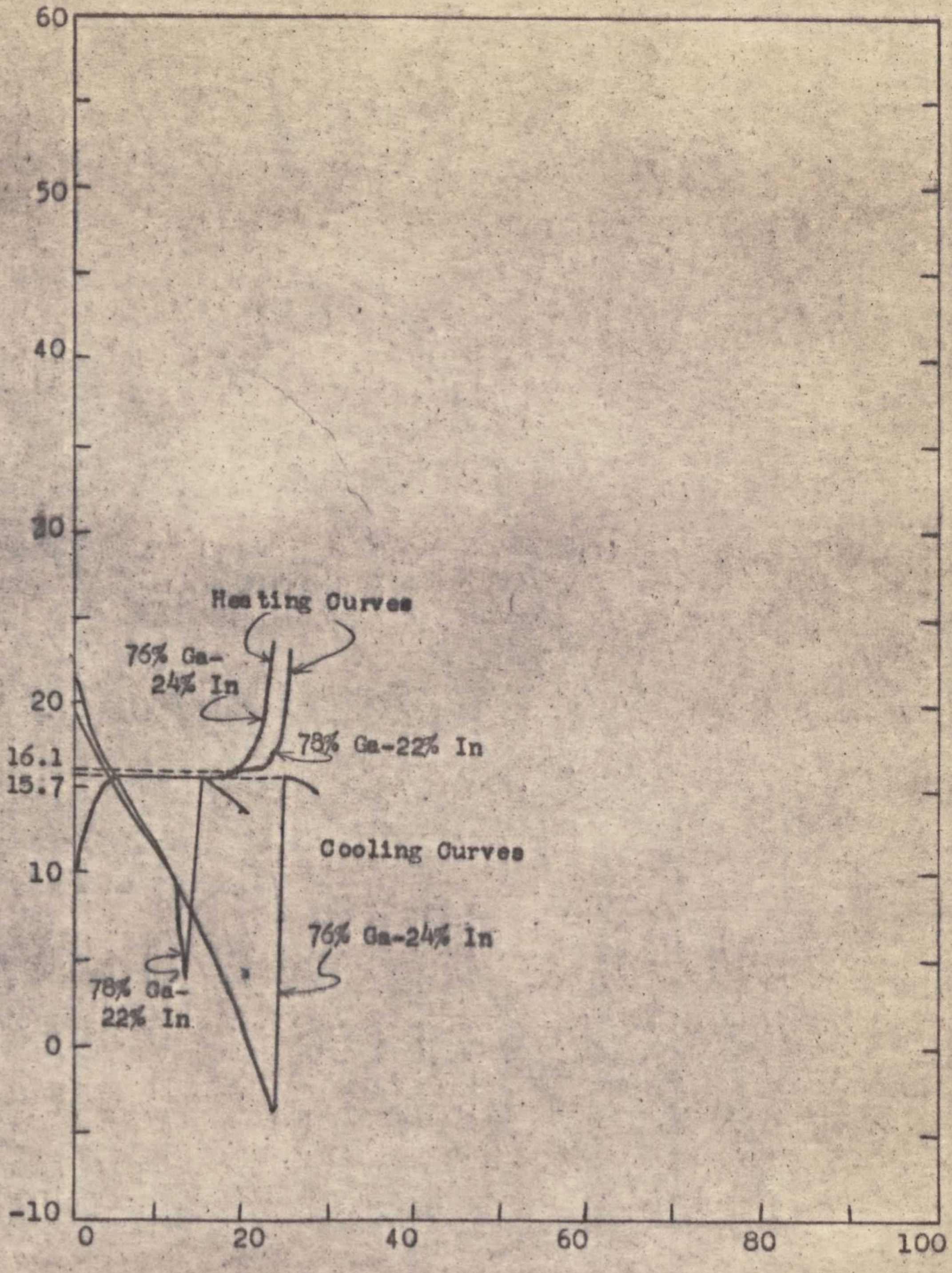


Fig. 13, Cooling and Heating Curves.

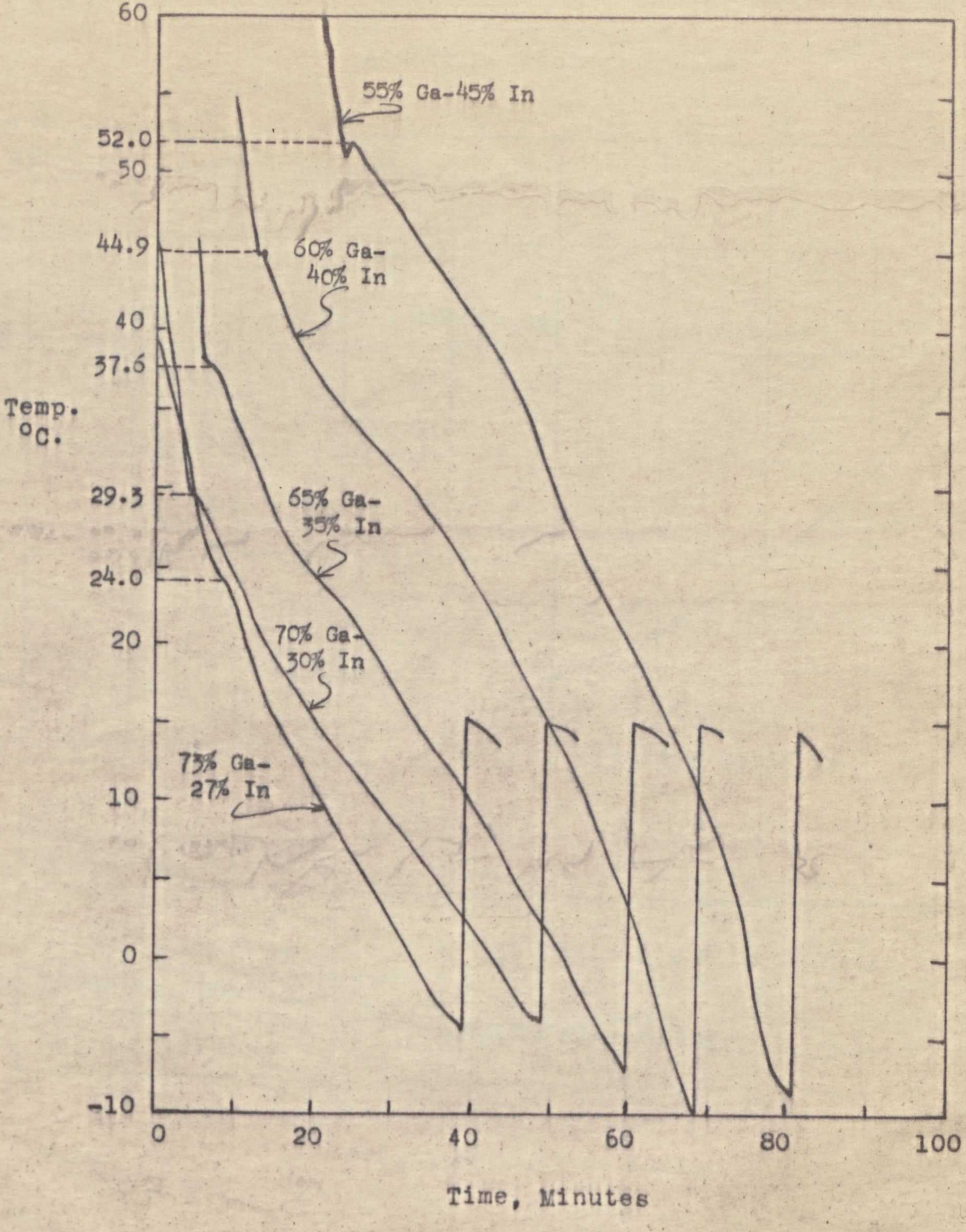


Fig. 14. Ga-In Cooling Curves.

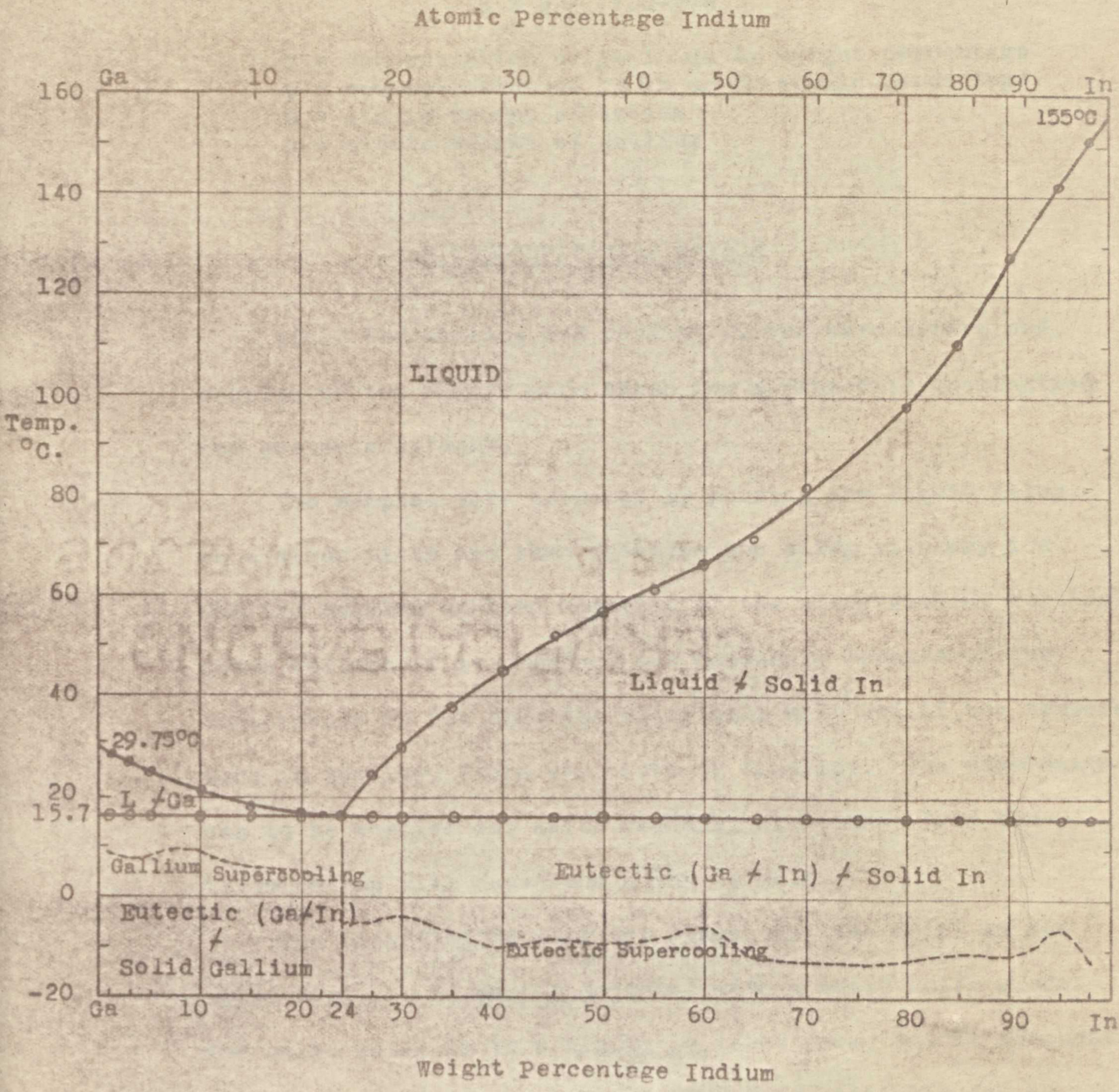


Fig. 15. Equilibrium Diagram for Ga-In Alloys

$$X = \frac{100 \times p \times b}{p \times b + (100-p)a}$$

X = concentration of In in Ga by weight percentage
p = concentration of In in Ga by atomic percentage
b = atomic weight of indium
a = atomic weight of gallium

MICROSCOPIC EXAMINATION

After the heating and cooling curves were determined, samples of the alloys were taken for microscopic examination and photomicrography.

The samples were prepared by pouring the liquid alloy on a glass plate and then freezing the alloy with dry ice. The ice backing enabled handling of the alloy without melting. Close control of temperature was necessary because if the temperature is too high the alloy will melt and if the temperature is too low, frost will form on the alloy. The examination has to be carried out quite rapidly, since heat from the illumination will cause the alloy to melt.

The liquid alloy will wet glass, but the metal in the solid form can be easily detached with a sharp knife blade. The solid metal is in a highly polished form, but it frequently contained air voids, which may have been partially due to imperfections in the glass plate.

The Bausch and Lomb type of metallograph equipped with a carbon-arc illuminating source was used for visual examination

Fig. 16. Microstructure of pure gallium.

Fig. 17. Microstructure of 15% Ga-85% In alloy.

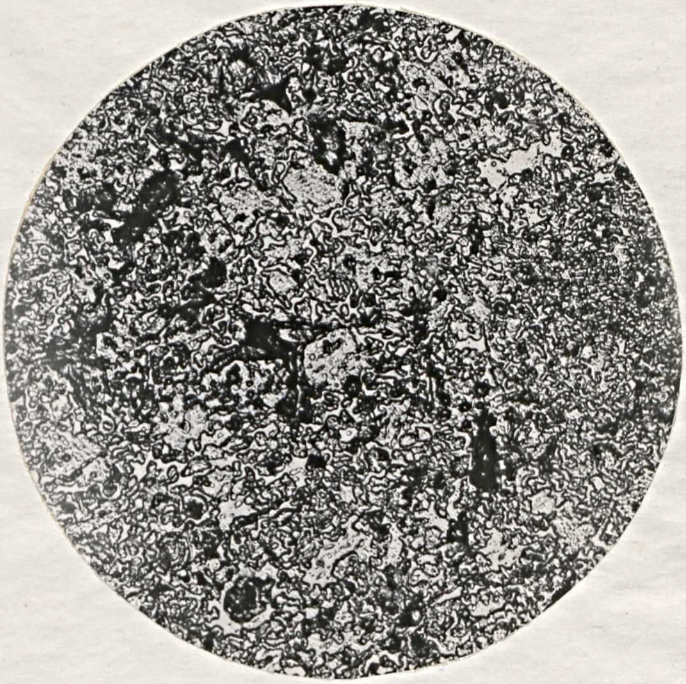


Fig. 18. Microstructure of eutectic alloy.

Fig. 19. Microstructure of 50% Ga-50% In alloy.

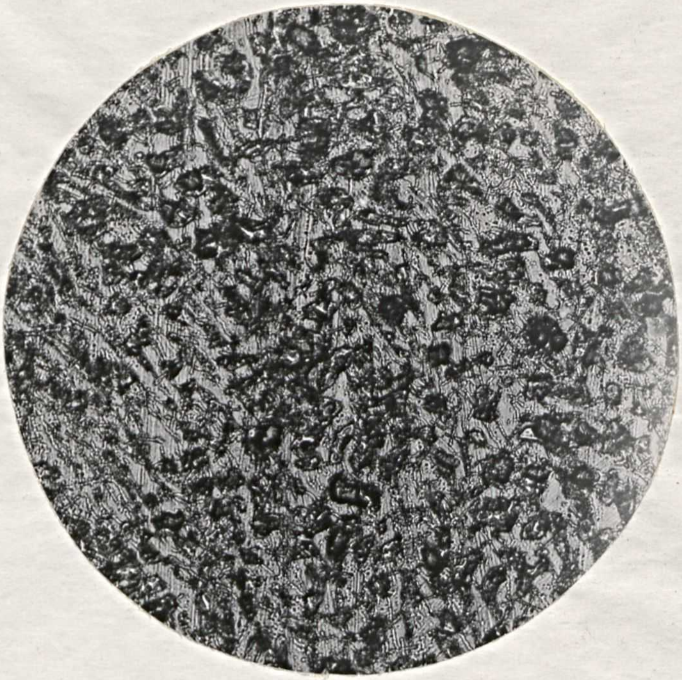


Fig. 20. Microstructure of 75% In-25% Ga.

Fig. 21. Microstructure of 95% In-5% Ga alloy.

and for the permanent recording of metallographic structures. Microstructures of a number of alloys are shown in Figs. 16 to 19. Etching of the samples was tried, but unsuccessfully.

ELECTROLYTIC RECOVERY OF GALLIUM AND INDIUM

An important part of the experimental work involved the recovery of pure indium and gallium from their alloys. The recovery of gallium was especially important because of the price and scarcity of the metal.

The gallium-indium alloys can be dissolved in HCl, HNO_3, or aqua regia. The action is slow but can be made to take place at a faster rate by heating.

Indium will plate out of an acid solution but gallium will not; therefore, the indium can be plated out, leaving the gallium in solution.

The acid solution was electrolyzed between thin-sheet indium cathodes and nickel anodes at 0.3 to 0.5 amperes at 4 volts. The plated indium metal was melted down and cast in appropriate form.

After the indium was plated out, the solution was made basic with KOH. Gallium hydroxide precipitates at a pH of about five and is redissolved at a pH of about eight. A carbon electrode was used as the anode, and a nickel wire was used as the cathode. The solution was kept warm enough to keep the gallium in liquid form so that it would drop off of the nickel cathode into a small crucible, which was placed in the solution below the nickel electrode. About five amperes at five volts was used to electrolyze the solution.

DISCUSSION AND CONCLUSION

The critical points determined by the heating and cooling curves show gallium and indium to be completely soluble in the liquid state and completely insoluble in the solid state. Curves were not constructed for alloys containing less than one per cent indium or two per cent gallium; therefore, it is possible that there might be a slight solubility of gallium in indium or indium in gallium.

Irregularities in the cooling and heating curves between the critical points were due to the use of different rates of cooling and heating. Fig. 4 illustrates the general procedure used in cooling and heating the alloys.

Supercooling caused considerable difficulty in determining the critical points for the liquidus line in the region between 85 per cent gallium and 76 per cent gallium. In this range there are two phases that supercool -- the solid gallium phase and the eutectic phase. The temperatures of the liquidus and the solidus are very close in this region, which made it difficult to determine the exact point where the alloy began to freeze. However, the heating curve showed a definite point for the solidus and also at a slightly higher temperature another inflection in the curve, which was taken as the critical point for the liquidus.

The reason that the temperature did not rise to the freezing temperature of the eutectic after supercooling, with the exception of the eutectic alloy, was that part of the heat of fusion evolved was absorbed by the solid indium phase. Stirring, which was noticed to reduce supercooling, was difficult at temperatures below 15 degrees Centigrade, since the solid indium phase has been precipitated at this temperature. With alloys containing a high percentage of indium, the solid indium made it impossible to stir the mixture below 15 degrees Centigrade. In these alloys the liquid eutectic occupied the voids in a solid indium network.

The cooling curves also show that indium supercools to a slight extent, but this supercooling was not large enough to cause any difficulties.

Superheating, which is the reverse phenomenon of supercooling, was not noticeable in the gallium or gallium-indium alloys.

In general, for alloys containing more than 24 per cent indium, the critical points of the heating curves were used to determine the solidus line and the critical points of the cooling curves were used to determine the liquidus line. Supercooling prevented the determination of the solidus on the cooling curves. Probably the large diffusion power of indium prevented any inflection on the heating curves for the liquidus.

The iron-constantan thermocouple was suggested as a means for the analysis, but it was considered that the analysis could be more adequately and conveniently carried out with mercury thermometers because of the low temperatures used, the corrosive properties of gallium and the necessary protection that would be required for the thermocouple leads.

As has been previously mentioned, gallium wets glazed porcelain and glass, but this property of gallium did not interfere with the accuracy of our determinations because of the large smaples used and the frequent stirring of the melt.

Microscopic examination and photomicrography were difficult operations because of the low-melting temperatures of the alloys. Photomicrographs for the alloys are shown in Figs. 16 to 21. The method of preparing these photomicrographs has been discussed under the experimental work for this investigation.

Much more experimental work will be required before it will be possible to accurately interpret the structure of these alloys from their photomicrographs, although the eutectic mixture and the solid phases of gallium and indium are distingquishable. A suitable method of etching these specimens would help to bring out the structural properties.

Further investigations to prevent supercooling of gallium-indium alloys would be a definite aid in accurately determining critical points on the liquidus line.

ACKNOWLEDGMENTS

I wish to express my gratitude and appreciation to Dr. J. George Grunenfelder, Professor of Metallurgy, for proposing the problem and for guidance in carrying out the investigation. I wish also to express my thanks to Professors Curtis L. Graversen and Ralph I. Smith for helpful suggestions and encouragment.

APPENDIX

DATA FOR HEATING AND COOLING CURVES

(Only the data near critical points is listed)

50% In-50% Ga

Cooling Curves

Time	Temp(°C)
4'07"	58.0
30	57.0
50	56.5
5'10"	56.0
30	56.0
45	56.5
6'00"	56.6
15	56.6
30	56.3
43	56.0
7'23"	55.5
40	55.0
8'32"	54.0
59'00"	0.0
78'00"	-4.0
78'29"	-9.0
45	14.6

Heating curves

Time	Temp(°C)
9'00"	15.2
15	15.3
30	15.4
45	15.5
11'00"	15.6
45	15.7
21'20"	15.8
23'30"	15.9
24'00"	16.5
07	17.0
12	17.5
18	18.0
30	19.0
57	21.0
25'13"	22.0
30	23.0
47	24.0

55% In-45% Ga

15'15"	61.3
30	61.2
55	61.1
17'15"	60.8
18'00"	60.6
55	60.0
20'15"	59.0
58'00"	0.0
60'45"	-5.0
64'30"	-8.0
40	15.0

6'15"	15.0
45	15.5
7'05"	15.6
25	15.7
17'00"	16.0
15	17.0
30	19.0
18'00"	22.0
10	23.0
20	24.0
35	25.0

Cooling Curves		Heating Curves	

60% In-40% Ga

Time	Temp(°C)	Time	Temp(°C)
7'40"	64.8	7'30"	15.6
45	66.2	55	15.7
8'10"	66.0	17'45"	15.8
30	65.8	55	16.0
40	65.5	18'30"	17.0
9'10"	65.0	38	18.0
27'20"	0.0	55	20.0
28'10"	-5.0	19'05"	21.0
22	-6.0	15	22.0
40	14.7	25	23.0

65% In-35% Ga

Time	Temp(°C)	Time	Temp(°C)
11'30"	72.0	6'30"	15.0
12'20"	71.0	7'00"	15.5
50	70.8	20	15.6
14'10"	70.6	45	15.7
20	70.5	12'20"	15.8
15'05"	70.0	14'55"	15.9
45	69.8	15'10"	16.0
16'30"	69.5	45	16.5
52'10"	0.0	40	20.0
53'55"	-5.0	55	22.0
63'30"	-12.0	17'15"	24.0
45	14.4	25	25.0

70% In-30% Ga

Time	Temp(°C)	Time	Temp(°C)
6'20"	79.0	5'20"	15.5
55	78.0	6'00"	15.7
7'35"	77.0	11'00"	15.8
8'15"	76.0	12'00"	15.9
35	76.2	15	16.0
50	76.0	13'15"	19.0
9'15"	75.7	25	20.0
55	75.0	45	22.0
11'40"	74.0	55	23.0
51'45"	0.0	14'05"	24.0
63'00"	-4.0	15	25.0
72'00"	-12.6	55	28.0
15	14.2	15'25"	30.0

75% In-25% Ga

Cooling Curves		Heating Curves	
Time	Temp(°C)	Time	Temp(°C)
5'55"	86.0	5'40"	15.0
30	85.0	6'30"	15.5
55	84.0	7'00"	15.6
6'20"	83.0	15	15.7
50	82.0	11'40"	15.8
7'20"	81.5	13'40"	16.0
30	81.8	14'15"	16.5
8'00"	81.7	25	17.0
30	81.0	35	18.0
9'35"	80.0	45	19.0
45'15"	0.0	15'05"	21.0
46'15"	-5.0	15	22.0
53'00"	-13.0	25	23.0
50	12.0	35	24.0

80% In-20% Ga

3'20"	93.0	4'00"	12.0
55	92.0	15	13.0
4'25"	91.0	35	14.0
55	90.0	55	15.0
5'25"	89.0	5'30"	15.7
6'00"	88.8	8'15"	15.8
45	88.6	9'30"	15.9
7'15"	88.0	11'30"	16.2
8'05"	87.5	12'05"	16.5
45	87.0	30	17.0
9'50"	86.0	13'00"	20.0
42'40"	0.0	50	22.0
49'00"	-12.5	14'45"	27.0
18	11.8	15'20"	29.0

85% In-15% Ga

10'30"	98.0	5'15"	14.0
11'30"	97.0	30	15.0
30	97.8	45	15.7
12'00"	97.2	9'30"	16.0
15	97.0	12'40"	17.0
59'30"	0.0	13'00"	19.0
64'00"	-11.-	13'20"	21.0
10	12.5	50	23.0

Cooling Curves		Heating Curves	
Time	Temp(°C)	Time	Temp(°C)
90% In-10% Ga			
3'05"	112.0	4'05"	14.0
20	111.0	20	15.0
35	110.0	35	15.7
55	110.2	8'20"	15.8
4'10"	110.0	35	16.0
30	109.6	55	17.0
45'25"	0.0	9'05"	18.0
47'40"	-11.2	25	20.0
50	6.2	35	21.0
95% In-5% Ga			
3'12"	129.0	5'00"	13.0
27	128.0	20	14.0
45	127.5	40	15.0
50	127.7	6'00"	15.7
4'10"	127.3	7'15"	15.8
25	127.0	8'00"	16.2
5'10"	126.0	12	17.0
42'00"	0.0	40	20.0
35	-5.0	9'15"	23.0
50	-6.2	35	25.0
57	0.4	10'40"	30.0
98% In-2% Ga			
0'52"	143.0	3'05"	12.0
1'00"	142.0	20	13.0
10	141.2	40	14.0
15	141.8	55	15.0
40	141.5	4'20"	15.5
55	141.0	30	15.7
2'40"	140.0	50	16.0
25'10"	0.0	5'20"	18.0
28'00"	-13.0	37	19.0
10	-11.0	55	20.0

Cooling Curves		Heating Curves	
Time	Temp(°C)	Time	Temp(°C)
1% In-99% Ga			
20'20"	9.0	3'40"	14.0
40	8.8	4'10"	15.0
21'00"	28.3	40	15.7
23'20"	28.2	5'20"	17.0
24'20"	28.1	16'45"	28.0
25'50"	28.0	50	28.2
27'30"	27.8	17'20"	28.1
29'20"	27.5	50	28.2
		18'15"	28.3
		19'00"	28.4
		23'00"	29.0
		25'55"	30.0
		28'10"	40.0
3% In-97% Ga			
15'00"	7.4	4'10"	14.0
50	26.5	5'05"	15.0
16'40"	26.4	35	15.5
17'15"	26.3	55	15.7
18'40"	26.1	6'10"	15.9
19'00"	26.0	25	16.0
		14'10"	25.0
		50	25.5
		15'45"	26.0
		16'35"	26.5
		18'40"	27.5
5% In-95% Ga			
13'40"	16.0	4'45"	15.0
14'30"	15.2	5'50"	15.4
15'10"	24.7	6'15"	15.7
15	24.8	7'00"	15.9
30	24.9	8'20"	15.5
16'45"	24.8	9'55"	18.0
17'35"	24.7	10'45"	19.0
18'00"	24.6	11'40"	20.0
19'15"	24.5	12'50"	21.0
20'05"	24.0	14'00"	22.0

Cooling Curves		Heating Curves	
Time	Temp(°C)	Time	Temp(°C)
10% In-90% Ga			
17'55"	10.0	4'45"	15.0
18'00"	9.0	5'30"	15.3
35	21.3	6'35"	15.5
45	21.2	7'10"	15.6
19'10"	21.1	45	15.7
19'20"	21.0	9'05"	15.8
20'40"	20.5	50	15.9
		10'20"	16.0
15% In-85% Ga			
28'45"	6.0	6'05"	15.4
30'20"	5.4	55	15.5
31'00"	16.6	8'15"	15.6
45	16.7	10'00"	15.7
32'15"	17.5	12'00"	15.8
34'00"	17.0	13'20"	15.9
35'15"	16.5	14'00"	16.0
20% In-80% Ga			
14'22"	12.1	5'42"	15.0
51	12.5	8'05"	15.4
15'13"	13.0	9'05"	15.6
50	14.0	10'27"	15.7
16'15"	15.0	18'05"	15.8
17'00"	15.3	21'45"	15.9
18'10"	15.5	24'43"	16.0
20'35"	15.6	27'05"	16.1
32'00"	15.5	28'24"	16.2
37'20"	15.4	29'15"	16.3
42'15"	15.0	30'27"	16.5
47'10"	14.0	31'43"	16.8
22% In-78% Ga			
10'00"	11.5	4'05"	15.0
12'00"	10.0	6'00"	15.5
13'20"	3.7	7'25"	15.6
15'20"	15.5	8'45"	15.7
16'20"	15.3	14.15"	15.8
		18'00"	15.9
		19'40"	16.0
		20'55"	16.1

Cooling Curves		Heating Curves	
Time	Temp(°C)	Time	Temp(°C)
24% In-76% Ga			
3'00"	17.0	2'35"	13.0
4'10"	16.0	3'05"	14.0
5'30"	15.0	40	15.0
7'50"	13.0	4'50"	15.6
9'25"	12.0	5'40"	15.7
10'00"	11.0	11'00"	15.8
12'20"	10.0	15'50"	15.9
24'00"	-5.0	17'30"	16.0
20	15.7	17'55"	16.1
		18'10"	16.2
27% In-73% Ga			
7'10"	25.0	2'33"	15.0
23	24.5	3'35"	15.5
8'10"	24.0	55	15.6
9'25"	23.0	5'40"	15.7
10'15"	22.0	10'25"	15.8
39'00"	-5.0	45	16.1
12	15.3		
30% In-70% Ga			
4'03"	30.0		
20	29.5		
30	29.4		
40	29.3		
46	29.2		
56	29.0		
5'20"	28.5		
6'00"	27.5		
49'00"	-4.0		
15	15.0		
35% In-65% Ga			
1'50"	38.0		
2'00"	37.7		
05	37.6		
08	37.5		
25	37.4		
30	37.3		
45	37.0		
3'03"	36.5		
55'05"	-7.0		
18	14.8		

40% In-60% Ga

Cooling Curves		Heating Curves	
Time	Temp(°C)	Temp	Temp(°C)
2'10"	46.0		
18	45.5		
30	45.0		
40	44.8		
45	44.9		
3'35"	44.5		
4'02"	44.0		
59'10"	-10.0		
60'00"	14.8		

45% In-65% Ga

3'21"	51.0
30	55.0
40	50.3
55	52.0
4'40"	51.5
5'05"	51.0
61'50"	-8.5
62'10"	14.7

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