THE SLOW DECOMPOSITION OF AUSTENITE

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William J. Blyth

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THESIS

THE SLOW DECOMPOSITION OF AUSTENITE

by

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Introduction

Dr. Albert Sauveur has stated: "The transformation of austenite of eutectoid composition into pearlite, that is, of a solid solution into an aggregate, implies structual changes of momentous importance to steel metallurgists."[7] The steels used for the study of the decomposition of austenite as discussed in this paper are not of eutectoid composition, but do offer structual changes of equal interest, since the transformation is from a solid solution to an aggregate.

Three steels were studied in this investigation, namely; S. A. E. 1045, S. A. E. 2340 and one special steel. The analysis of the steels in the 1045 and 2340 classisfication are not available except for the carbon in the 1045, which is .39%; and the carbon, nickel and manganese in the 2340, which are .29%, 3.42% and .71% respectively. The analysis of the special steel is as follows.

Carbon	0.49%
Manganese	1.02
Sulfur	0.09
Phosphorous	0.015
Nickel	0.09
Chromium	0.62
Molybdenum	0.24
Silicon	0.25

The purpose of the investigation of these three steels was to determine the effect of the slow decomposition of austenite on on microstructure.

Austenite is defined as the solid solution of carbon and other elements in gamma iron. As a consequence each steel would have a different austenite, and should give a structure dependent on the composition of the steel.

The steels used are of nearly the same carbon content. However, since one is a plain carbon, another a nickel-manganese, and the third a special steel containing appreciable amounts of manganese, chromium and molybdenum, the effects of the different alloying elements on microstructure can be studied.

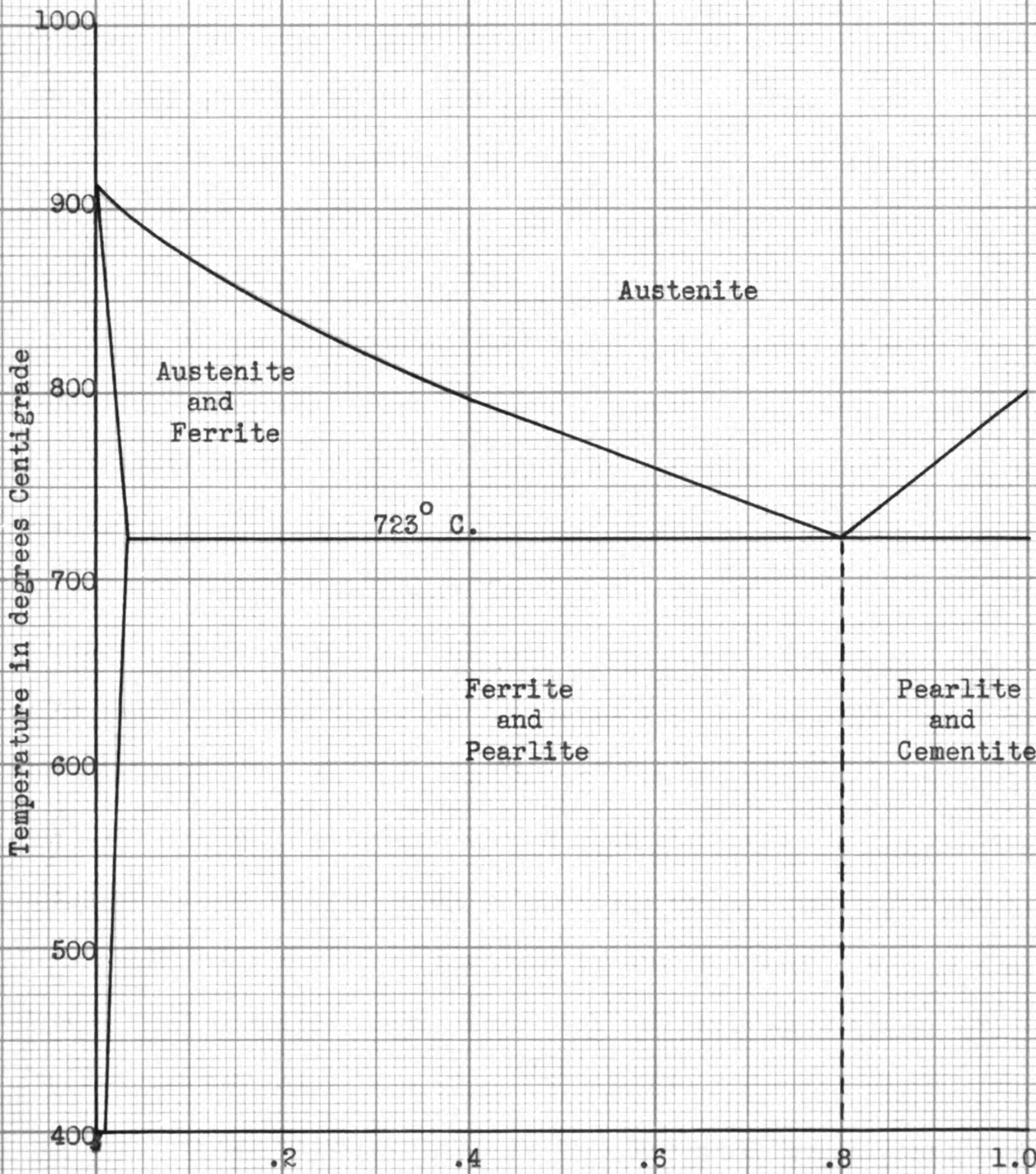
Discussion

Austenite has been defined as the solid solution of carbon and other elements in gamma iron. Gamma iron is an allotropic form of iron that is stable between 910 and 1400 degrees centigrade. Another allotropic form of iron is alpha iron. Alpha iron is stable at temperatures below 910 degrees centigrade. The term ferrite is applied to solid solutions in which alpha iron is the solvent. Cementite is the compound that carbon forms with iron, and is represented by the formula Fe_3C. Cementite contains 6.67% carbon by weight. Other elements might also form other carbides similar to cementite. Pearlite is the product of decomposition of austenite of eutectoid composition, and is made up of alternate thin lamellae of ferrite and cementite. The above terms have been defined in order that a uniformity of terminology will exist in this paper. In many cases these terms are very loosely used. All of the definitions are taken from the Metals Handbook published by the American Society for Metals.[3]

A portion of the iron-carbon equilibrium diagram, as taken from the Metals Handbook,[3] is shown in figure 1. This diagram shows the composition of the eutectoid of a plain carbon steel to be .80% carbon; and the point of complete transformation of austenite to its aggregate to be 723 degrees centigrade.

The temperature separating the austenite area from the area of austenite and ferrite is generally known as the A_3 temperature;

Figure 1
Iron-Carbon Equilibrium Diagram



but more specifically, in the case of cooling, the temperature at which ferrite starts to separate out from austenite is called the A_{r3} temperature. The temperature at which complete transformation has just taken place is the A_1, or more specifically, on cooling it is the A_{r1} temperature. Similarly, on heating the two temperatures are known as the A_{c3} and the A_{c1}. Under pratical conditions there is a lag in the attainment of equilibrium, and the transformation points, or critical temperatures, are found at lower temperatures on cooling than those that are given.[2]

In this investigation the steels that were studied are all approximately 0.4% carbon. Let us consider what takes place as a 0.4% carbon steel is cooled from the austenitic range.

At the temperature just above the A_{r3} austenite is the only constituent present. Just at the A_{r3} temperature there is an infinitely small amount of ferrite separated out from austenite, and the austenite has become richer in carbon by an infinitely small amount. As the cooling continues more ferrite separates out until at a temperature just above the A_{r1} the amount of austenite that is left is of eutectoid composition. At the point A_{r1} the pearlite, which is eutectoid, forms. At any point below this temperature there exists pearlite and ferrite in equilibrium with each other if the cooling was slow enough so that equilibrium could be attained. The amount of pearlite will depend on how much carbon is present, and in the case of a 0.4% carbon steel there will be nearly equal parts of ferrite and pearlite.

In the experimental work the Chevenard Thermal Analyser,

a direct type of dilatometer, was used to control the rate of cooling of the test specimens. The dilatometer is an instrument that records expansion-time-temperature data. From this data critical temperatures of steel may be found by making use of the fact that as a steel specimen goes through a critical temperature there is a change in its rate of expansion or contraction. For example, as a steel is heated it expands until the A_{c1} temperature is reached. At this temperature there is a sudden contraction caused by the change of space lattice as the alpha iron is changed to the gamma iron and pearlite goes into solid solution. The contraction of the specimen continues until all the ferrite is dissolved at the A_{c3} temperature and the specimen is completely austenitic. At this temperature the expansion again continues. As the specimen cools it contracts until the A_{r3} temperature is reached. Then there is an expansion until the A_{r1} temperature is passed when the specimen contracts. The expansion and contraction of the specimen is recorded by means of a lever system and a stylus which records on a revolving drum. This gives a continuous record of the expansion and contraction. In order that the temperature at any given time may be known, a standard pyros specimen that has a nearly constant coefficient of expansion over a working range is placed beside the test specimen and connected by a similar lever system to another stylus. Thus two curves are plotted simultaneously, one showing time vs. dilatation of the specimen and the other showing time vs. dilatation of the known standard. The temperature of the specimen at any given time can then be found by using a scale calibrated from the standard pyros specimen. A dilatation curve can then be plotted showing temperature in degrees centigrade vs. dilatation in units per unit, x 10^{-3}. Of course the specimen must be always the same length in order to have true dilatation in these units. The dilatometer used is calibrated for specimens 55 mm. long. In some cases specimens of other lengths have been used, and when this has been done I have called the contraction dilatation. This can be done because the form of the curve shows no change with change in specimen length; however such dilatation has no units but merely shows a comparison of length.

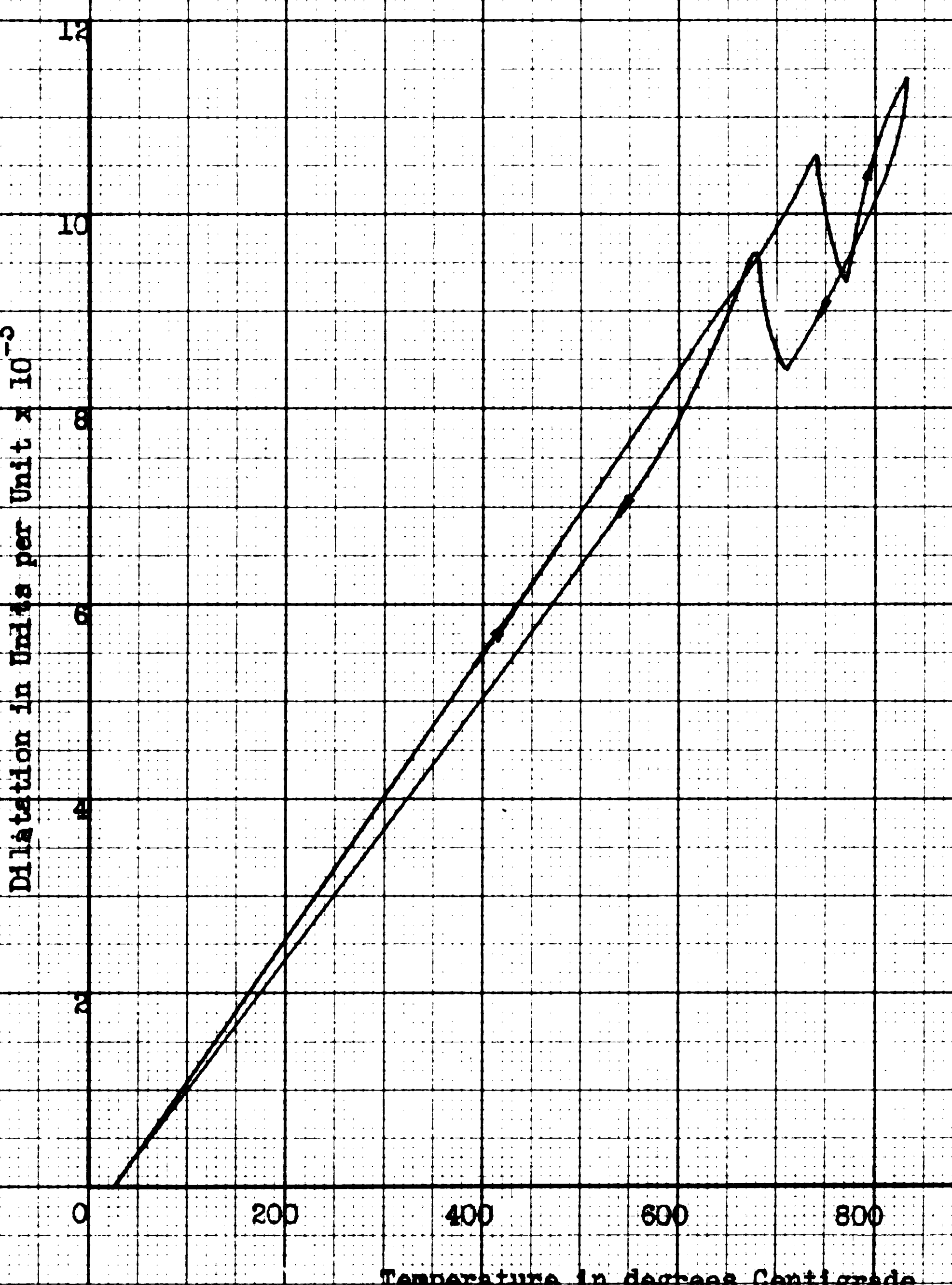
Figure 2 is a dilatation curve on standard S. A. E. 1090 specimen used to check the calibration of the instrument and to show the general nature of a dilatation curve. This curve shows the A_{r1} temperature to be 725 degrees centigrade. This checks the equilibrium diagram to 2 degrees, which is close enough because it is within the accuracy of the pyros standard.

Figures 3 and 4 illustrate a point brought out by Epstein who says: "The temperature at which some of the transformations take place is greatly affected by heating and cooling rates..."[3] This point must be remembered, because for the various cooling rates used the A_{r1} temperatures do vary.

Figure 5 is a dilatation curve on S. A. E. 1045 steel specimen 1. This specimen was heated to 870 degrees centigrade and then allowed to cool in the furnace of the dilatometer with the electric current turned off. This allowed the specimen to stay in the lower critical range for 1 minute.

In all cases in this paper the time of cooling through the

Figure 2
Dilatation Curve for Standard
1090 Specimen



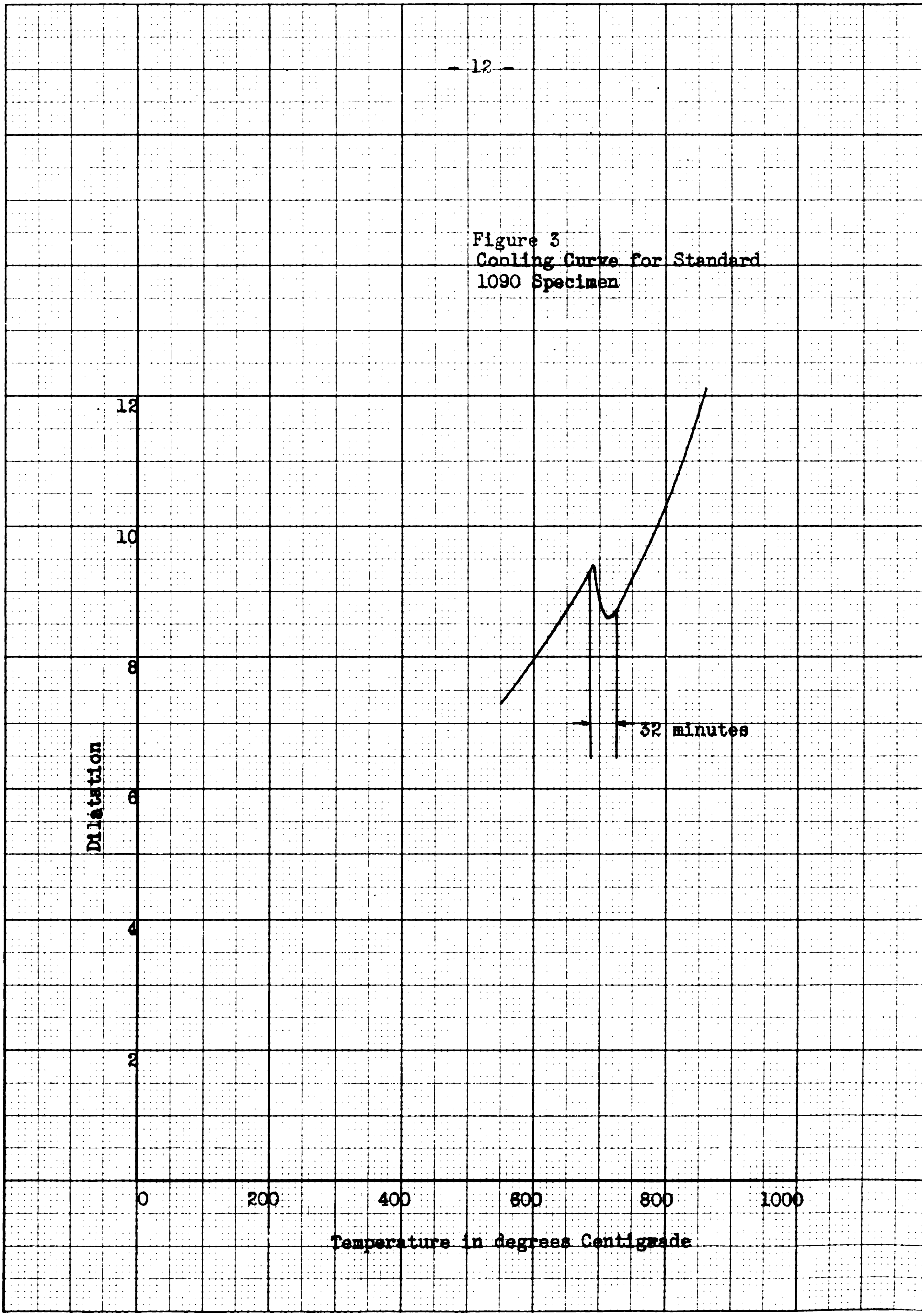


Figure 3
Cooling Curve for Standard
1090 Specimen
12
10
8
6
4
2
Dilatation
32 minutes
0
200
400
600
800
1000
Temperature in degrees Centigrade

Figure 4
Cooling Curve for Standard
1090 Specimen

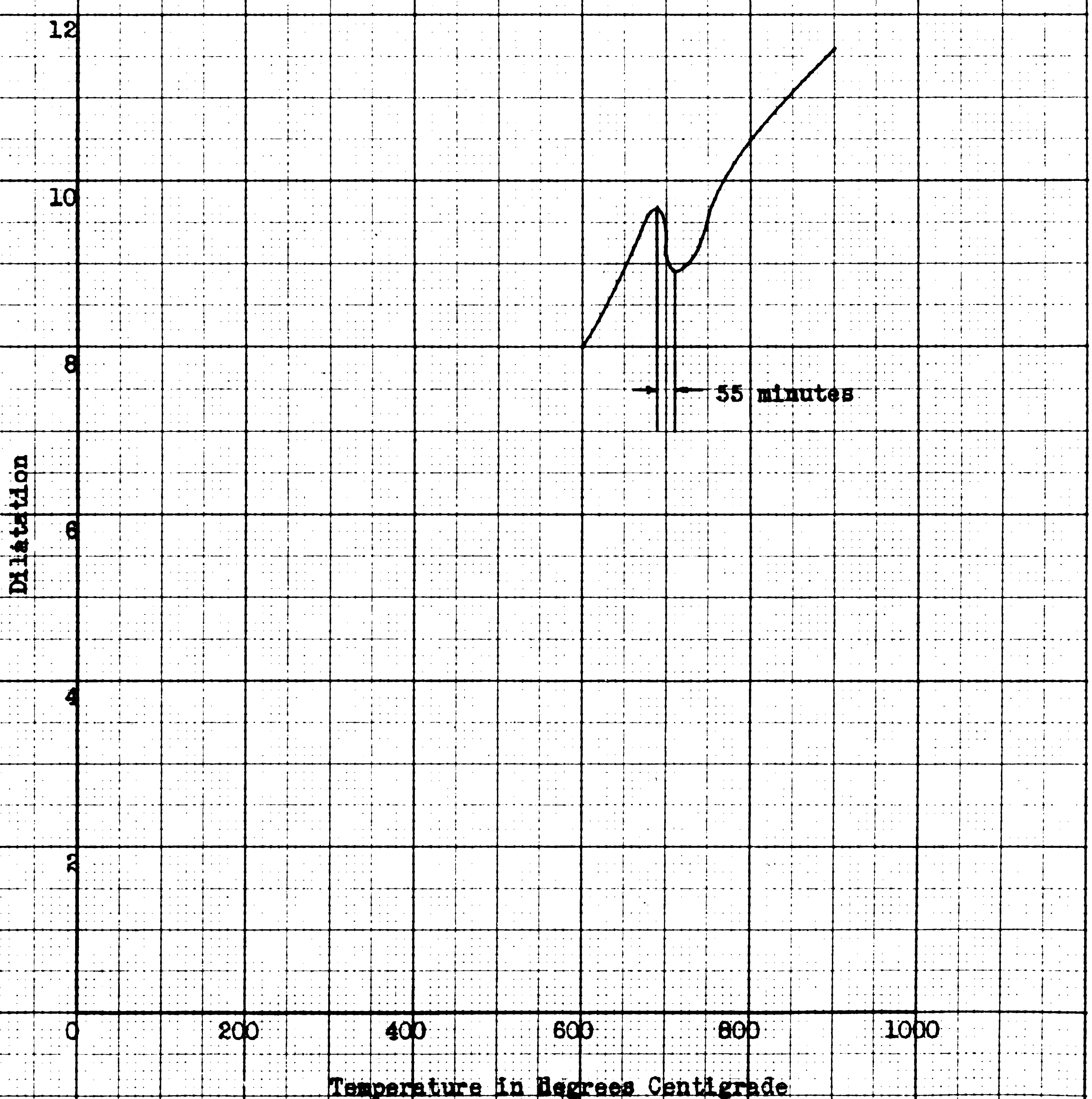


Figure 5
Dilatation Curve
1045 Steel
Specimen 1

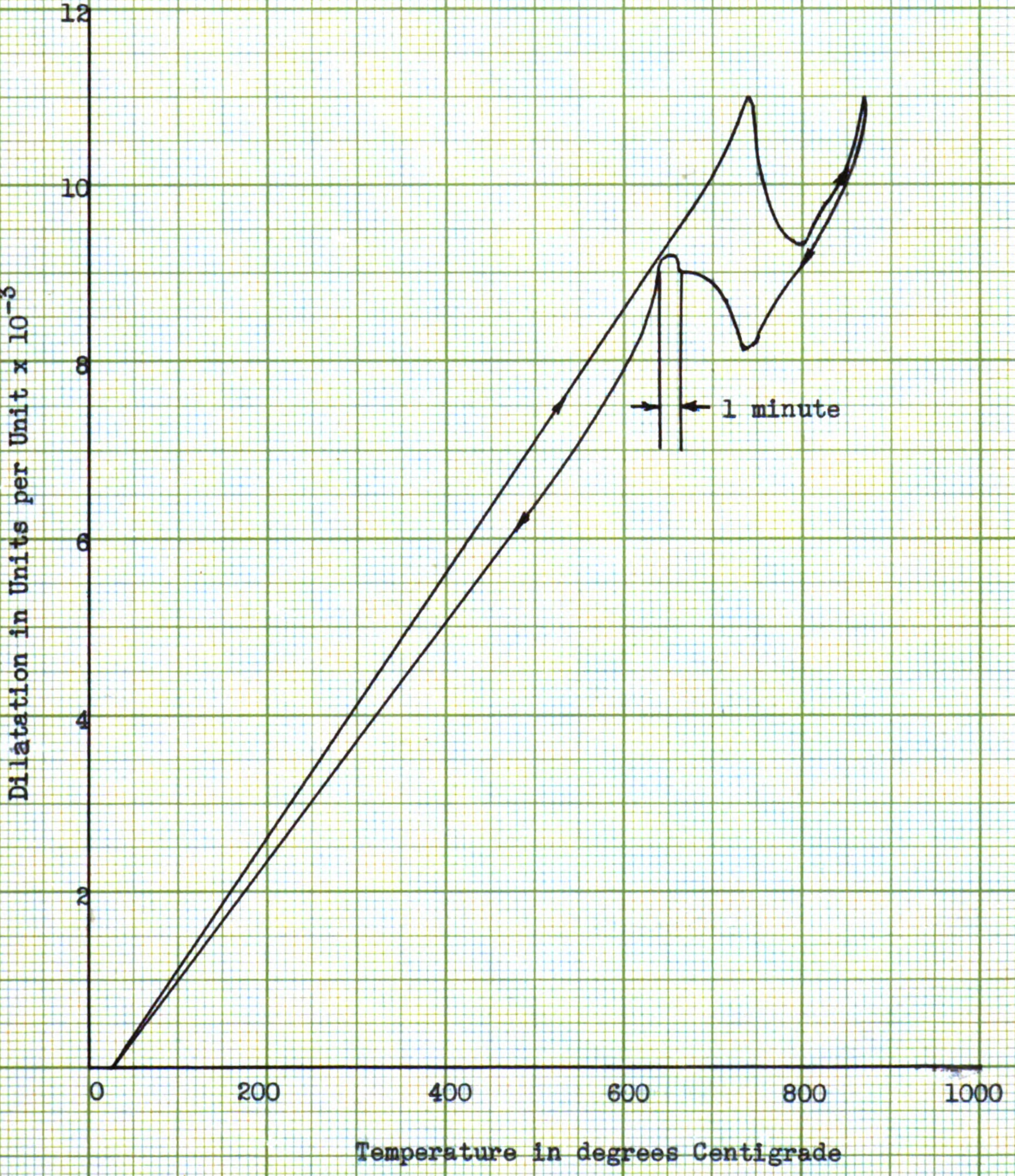
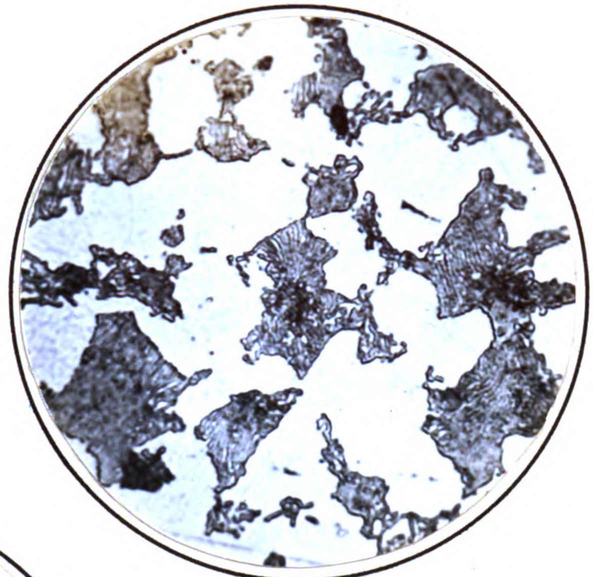
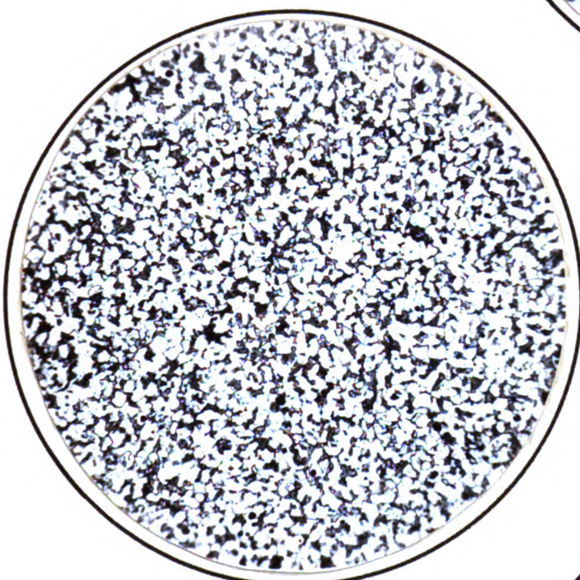


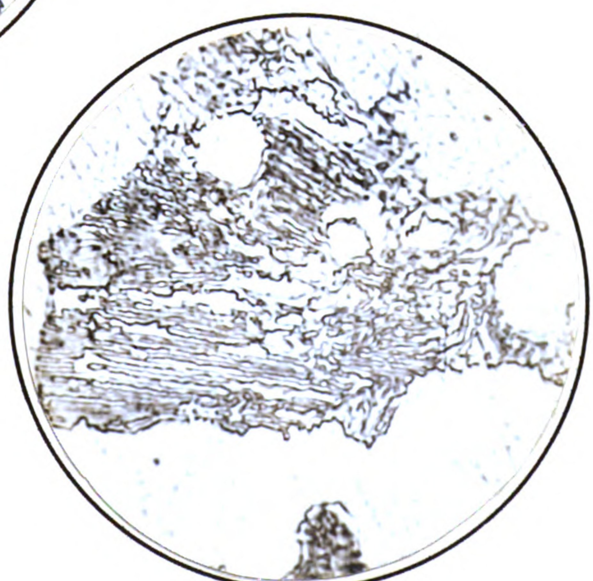
Figure 6 Specimen 1
1045 Steel Cooled through
lower critical for 1
minute. Picral etch.



800x



100x



2000x

lower critical is determined from the original curves of the dilatometer because they show more clearly where each transformation takes place.

Figure 6 shows photomicrographs of specimen 1. The photomicrographs were taken at 100, 800 and 2000 magnification using a 10x eye piece and a 24 mm, 0.2 N. A.; 4 mm, 0.85 N. A. and 1.8 mm, 1.30 N. A. oil immersion objective lenses respectively. The low magnification photomicrographs show that the specimen is in normal equilibrium, as there are definite areas of ferrite and pearlite in equilibrium with each other. The photomicrograph at 800 magnification does not resolve any of the detail of the pearlite, and this might classify it as fine pearlite. The photomicrograph at 2000 magnification does not resolve the pearlite very well, but it does show that it is made up of alternate lamallae of ferrite and cementite.

Figure 7 is a contraction-temperature curve on 1045 steel specimen 3. By means of a variable resistance in series with the furnace of the dilatometer the rate of cooling of the specimen in the furnace was controlled. In this case it took 15 minutes to go through the lower critical range. It may be noticed that the contraction-temperature curve is somewhat different from figure 5. Specimen 3 was not exactly 55 mm long and figure 7 does not indicate true expansion in definite units, but rather is a form of a cooling curve in which temperature is plotted against dilàtation in arbitrary units. Also the rate of cooling affected the general shape of the curve as it altered the temperature of transformation. Figure 8 shows photomicrographs of specimen 3. In this series the 800 magnification picture

Figure 7
Cooling Curve
1045 Steel
Specimen 3

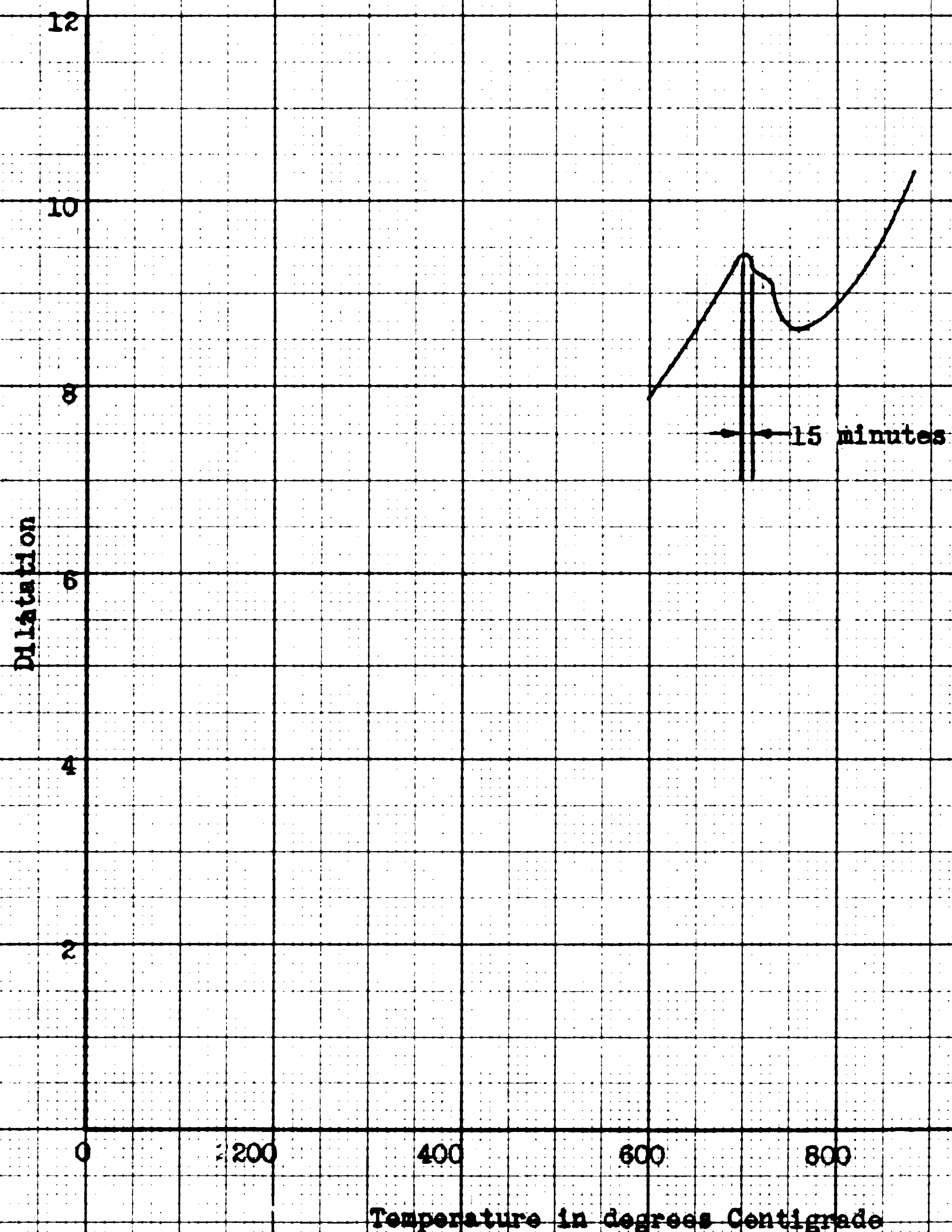
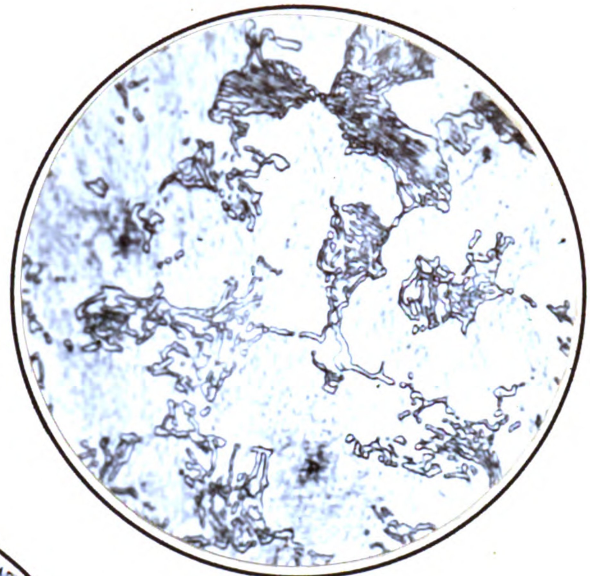
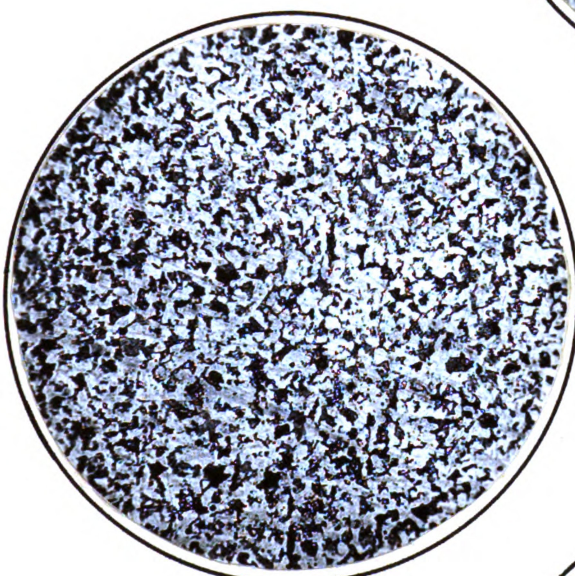


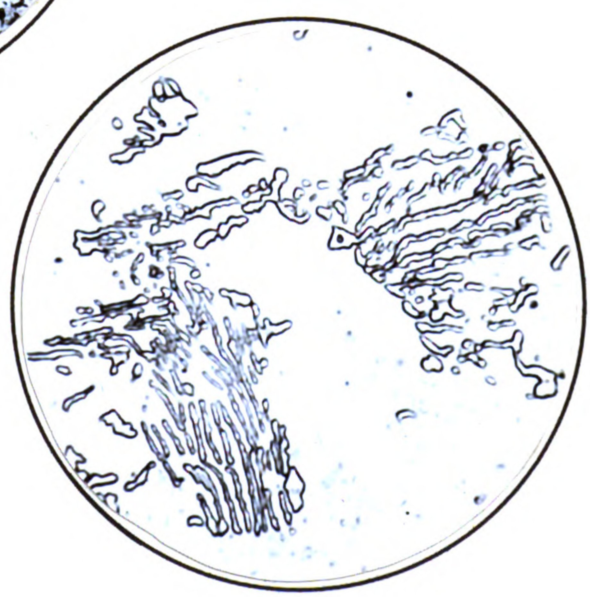
**Figure 8 Specimen 3
1045 Steel Cooled through
lower critical for 15
minutes. Picral etch.**



800x



100x



2000x

shows that the pearlite is not as fine, and can be resolved with the 4 mm objective lens. This indicates that the coarseness of pearlite depends somewhat on the rate of cooling. The 2000 magnification photomicrograph shows that the pearlite is not only coarser, but also is more broken up; and there seems to be a start toward spheroidization.

In order to determine if the structure of the pearlite is affected by holding the temperature between the A_{r3} and the A_{r1} temperature specimen 14 was heated to austenite and cooled slowly so that it was held 62 minutes between the upper and lower critical temperatures. Then it was furnace cooled so that it took 2 minutes to go through the lower critical range. The cooling curve is shown in figure 9 and the photomicrographs are shown in figure 10.

According to the theory of the equilibrium diagram all pearlite forms at the instant the specimen passes through the A_{r1} temperature. While the specimen is above this temperature only ferrite is precipitating out. Because of this there should not be much change in the type of pearlite when the specimen is held between the two critical temperatures. Figure 10 shows photomicrographs of specimen 14. The pearlite is, as would be expected, rather fine and no detail can be seen at 800 magnification. At 2000 magnification it is not very coarse, but the lamellae are somewhat broken up in contrast with figure 6. This would indicate that taking 2 minutes to cool, instead of 1 minute, as was done in figure 6, would cause the laminations to break up considerably, but still not cause an increase in coarseness.

Figure 11 is a contraction-temperature curve of specimen 15,

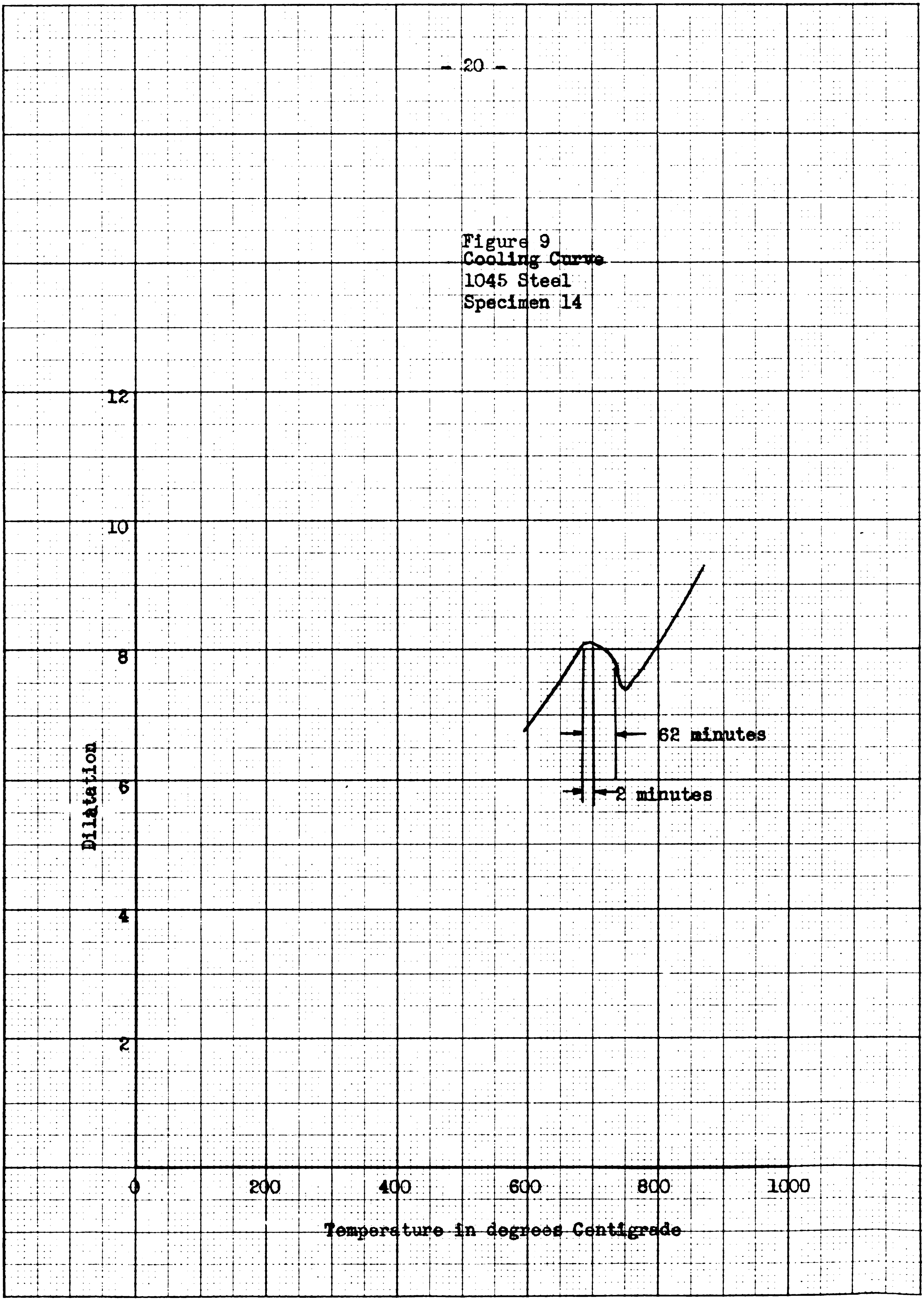
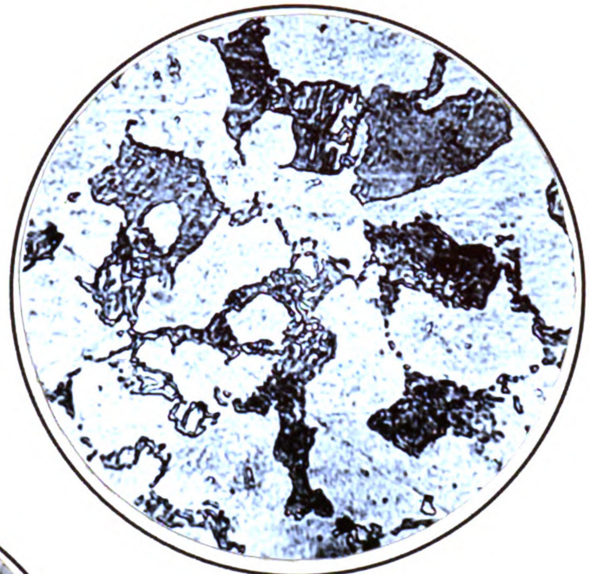
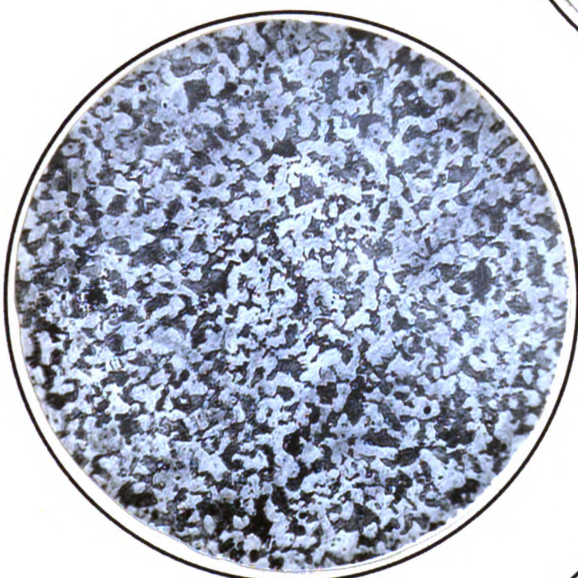


Figure 9
Cooling Curve
1045 Steel
Specimen 14
62 minutes
2 minutes
Dilatation
12
10
8
6
4
2
0
200
400
600
800
1000
Temperature in degrees Centigrade

Figure 10 Specimen 14
1045 Steel Cooled through
lower critical for 2
minutes. Picral etch.



800x



100x

2000x

which was cooled 40 minutes through the lower critical range. Figure 12 shows photomicrographs that indicate that spheroidization has started but is not yet complete, and that the specimen is not uniform in regard to the coarseness of the pearlite.

Figure 13 shows the contraction-temperature curve for specimen 5, which was cooled for 84 minutes through the lower critical range. This specimen shows a very marked increase in size of the pearlite particles, as shown by figure 14. The 100 magnification photomicrograph shows that there is still the same amount of pearlite, but that the alternate lamellae of ferrite and cementite which form the pearlite are different. This may be caused by the precipitation of more ferrite from austenite so that the composition of the eutectoid is richer in carbon.

Figure 15 is the contraction-temperature curve for specimen 17, which was cooled for 200 minutes through the lower critical range. The microstructure of this specimen, as shown by figure 16, has very large particles of eutectoid, and there are no pearlite areas that follow the definition of pearlite as given by the Metals Handbook.[3] This eutectoid structure could be called free carbide. Even at 100 magnification the detail of this speroidal structure can be seen.

To check these photomicrographs specimen 7 and 16 were cooled very slowly taking 204 and 213 minutes respectively to go through the lower critical, as shown in figures 17 and 19. The photomicrographs in figures 18 and 20 show the same general type of eutectoid structure.

It would seem evident that after cooling 200 minutes, or

Figure 11
Cooling Curve
1045 Steel
Specimen I5

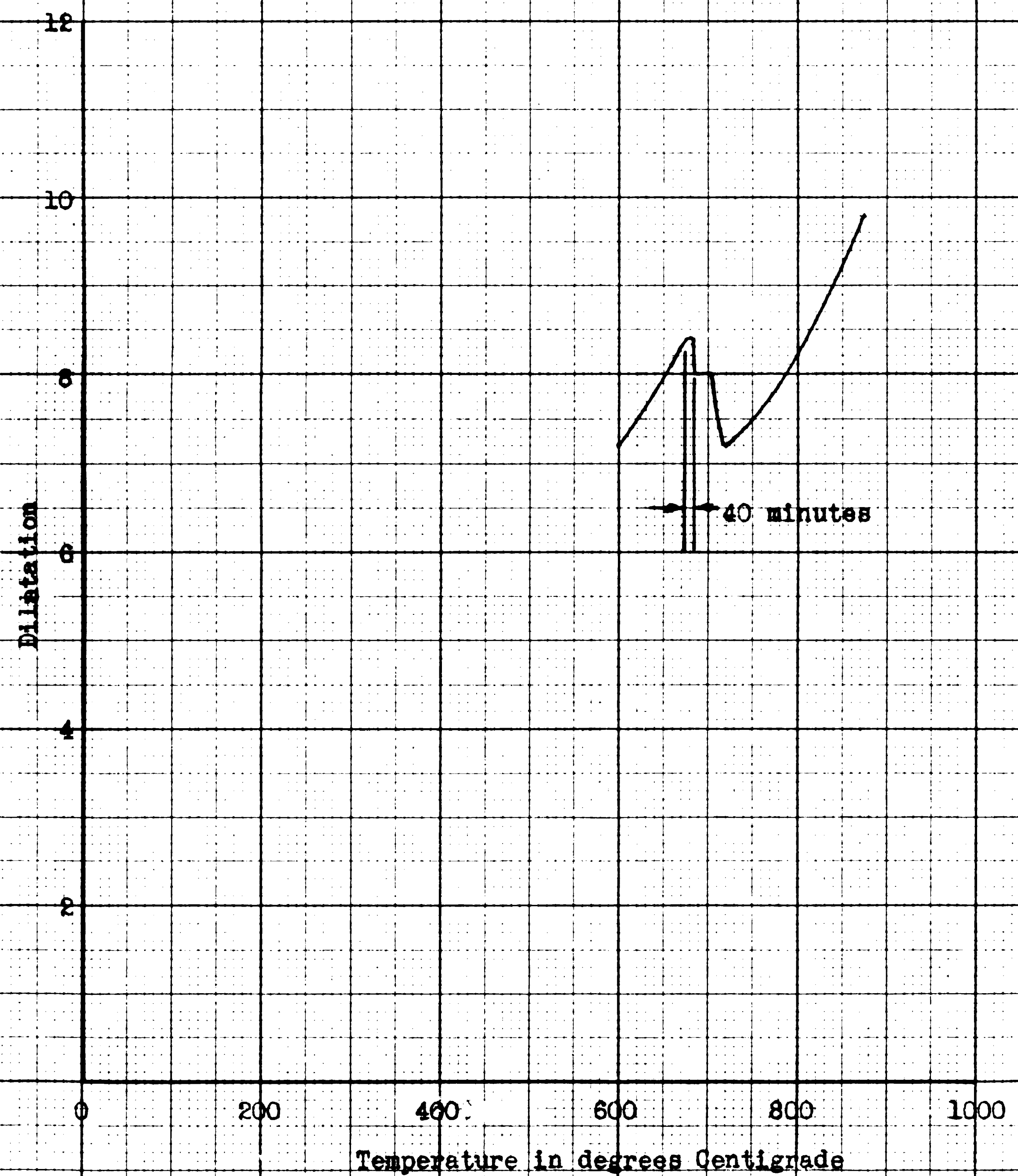
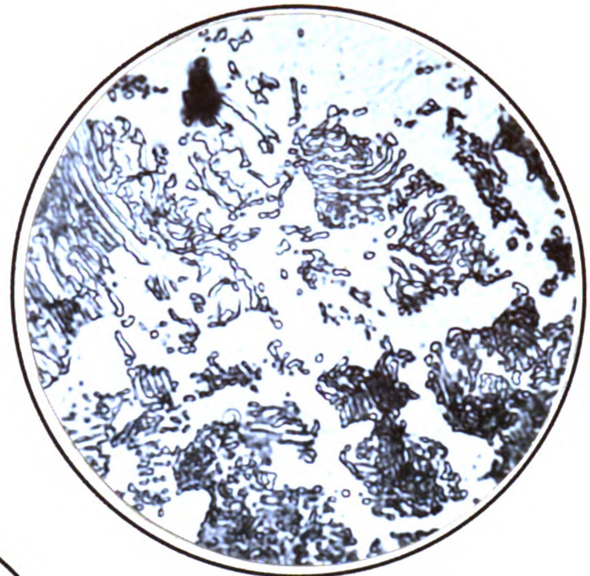
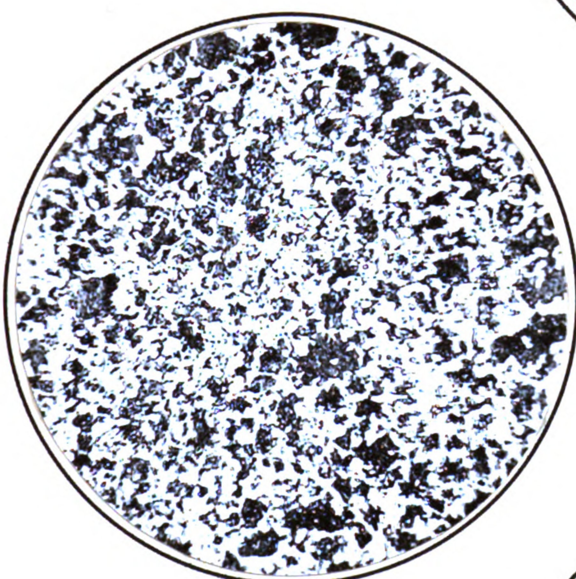


Figure 12 Specimen 15
1045 Steel Cooled through
lower critical for 40
minutes. Picral etch.



800x



100x

2000x

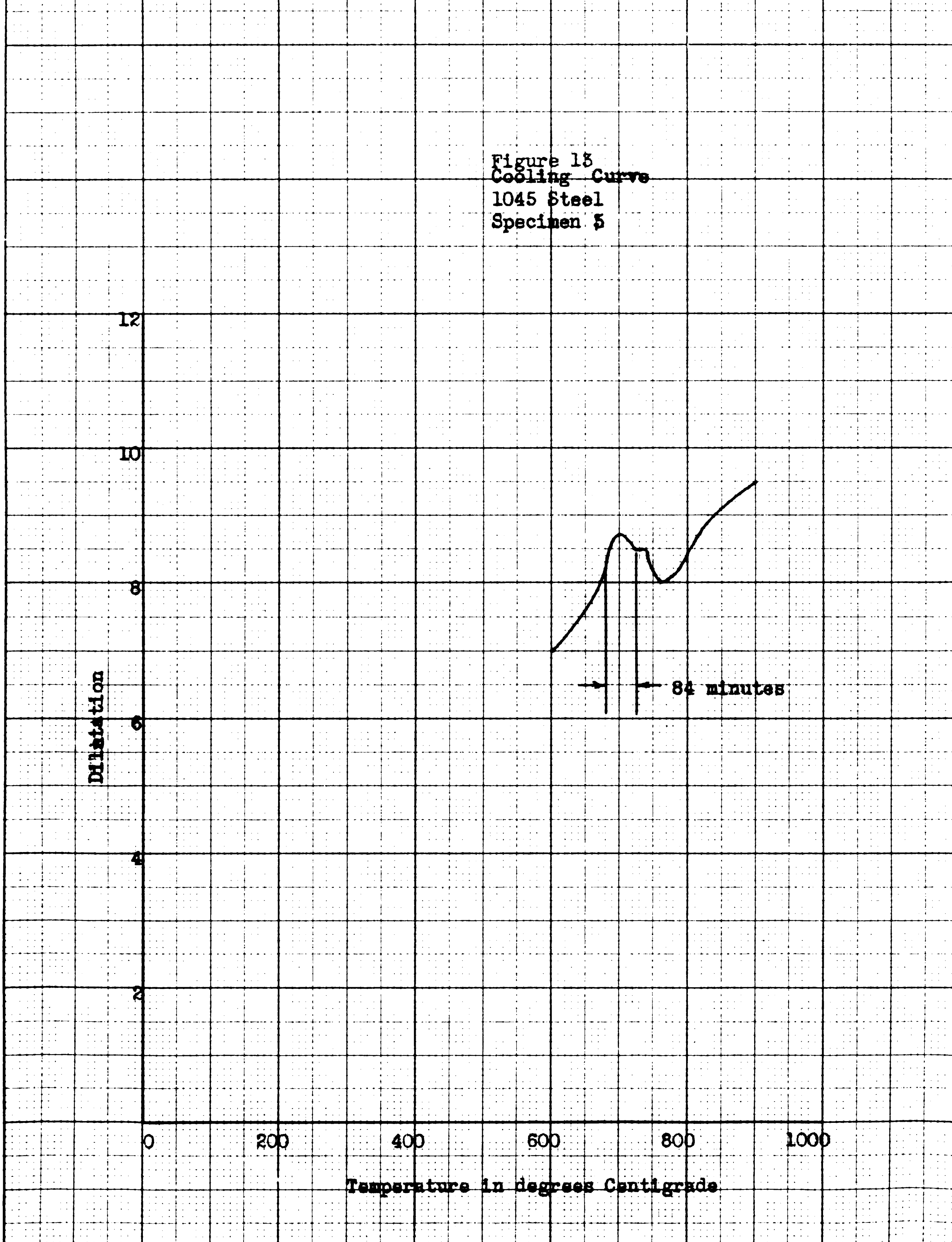
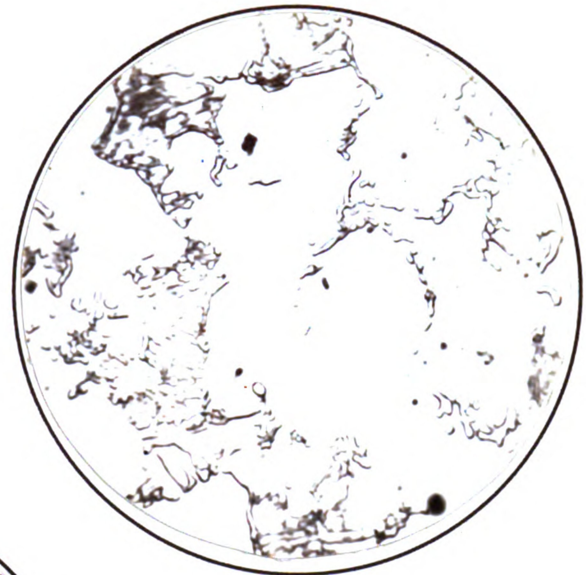
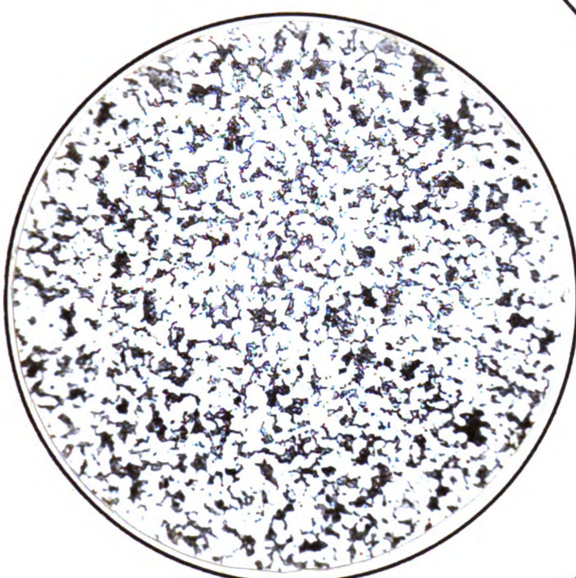


Figure 13
Cooling Curve
1045 Steel
Specimen 5

Figure 14 Specimen 5
1045 Steel Cooled through lower critical for 84 minutes. Picral etch.



800x



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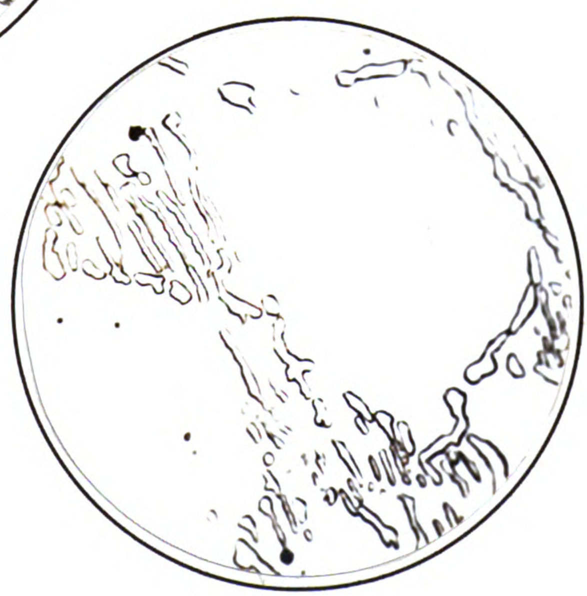

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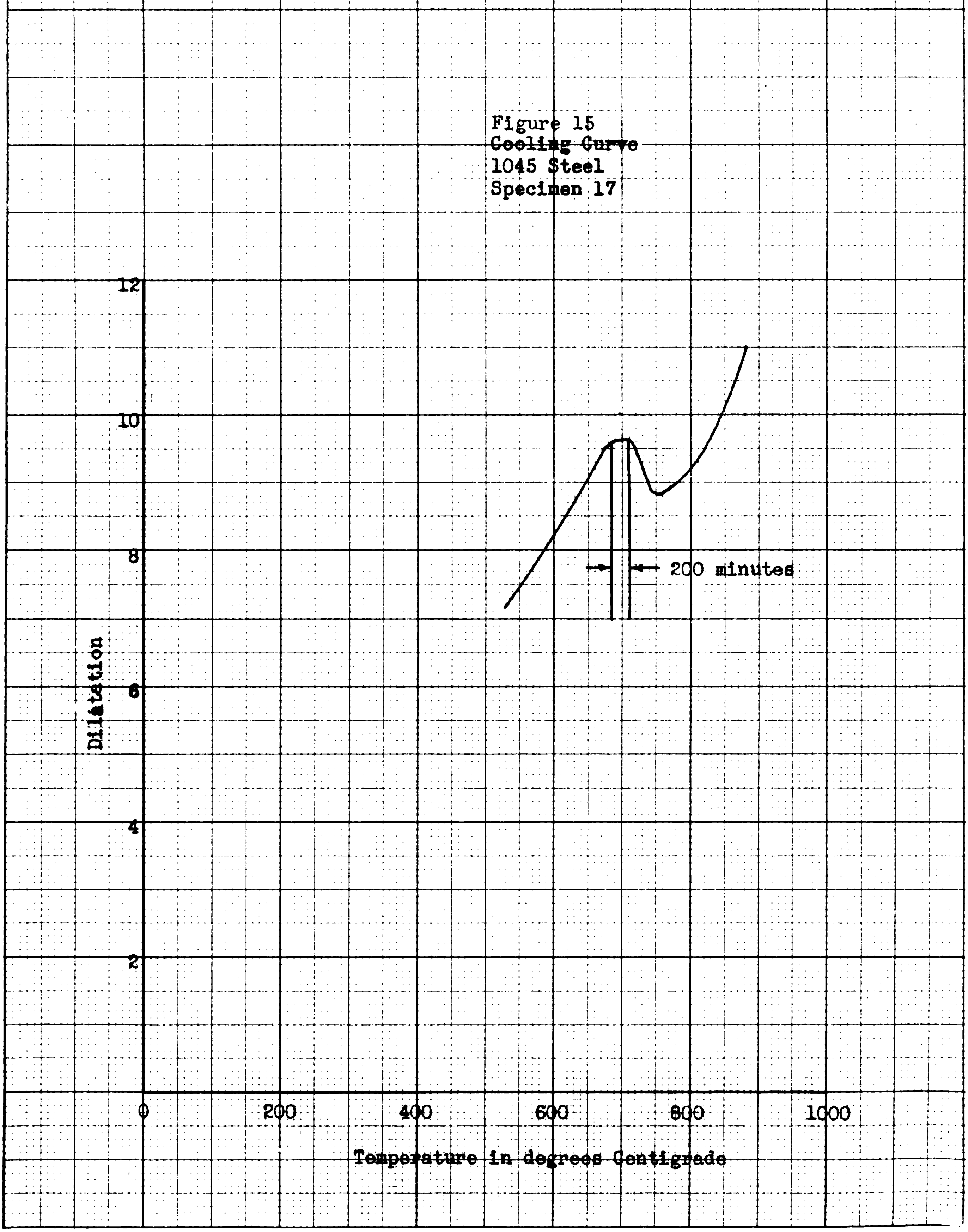
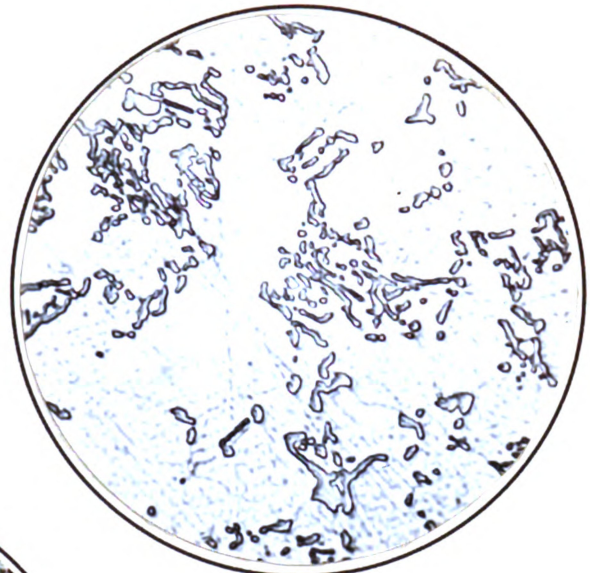
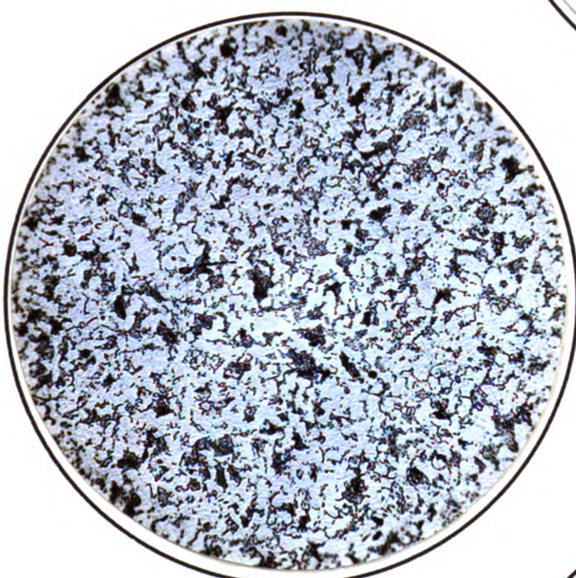


Figure 15
Cooling Curve
1045 Steel
Specimen 17

**Figure 16 Specimen 17
1045 Steel Cooled through
lower critical for 200
minutes. Picral etch.**



800x



100x

2000x

Figure 17
Cooling Curve
1045 Steel
Specimen 7

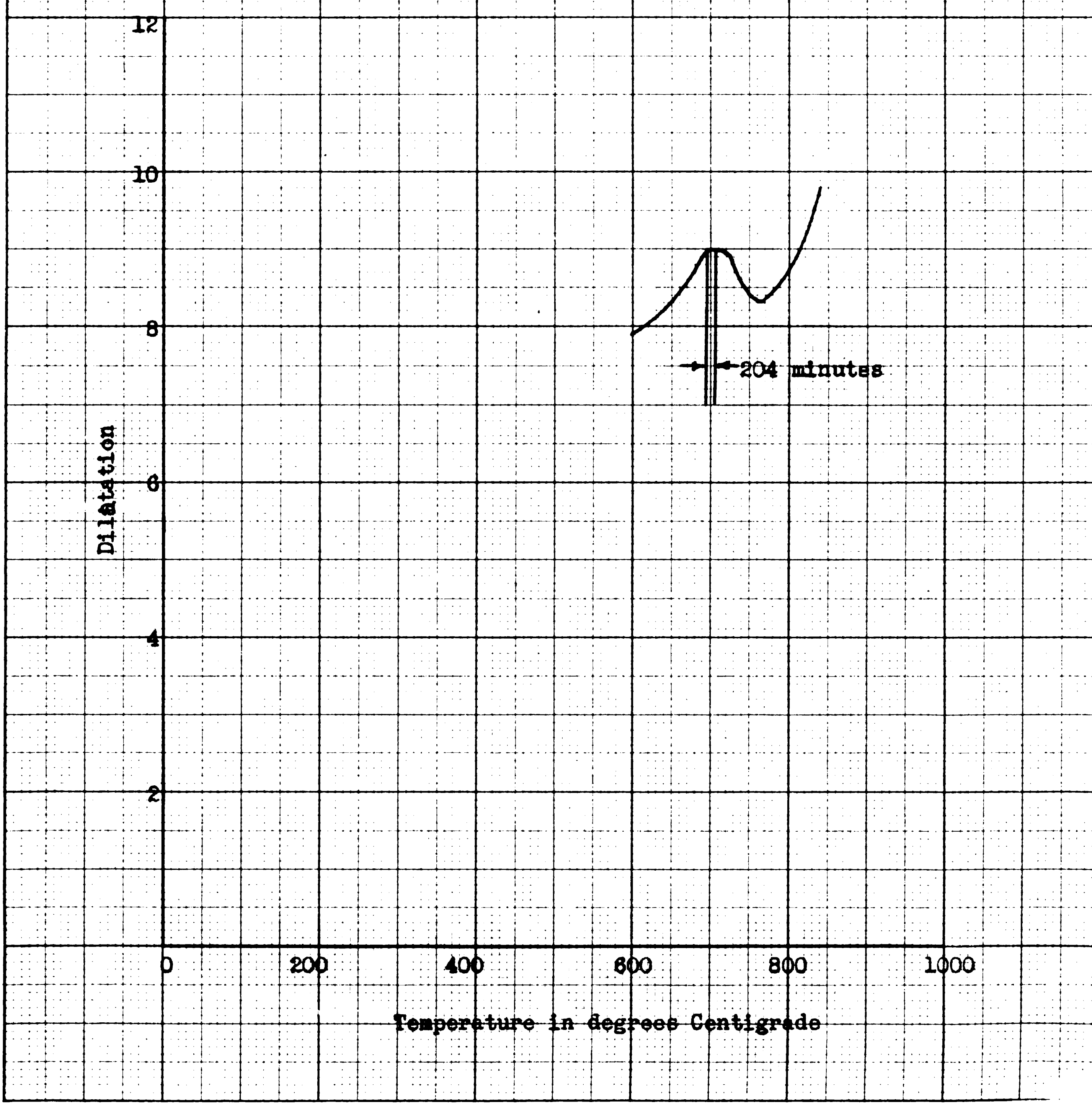
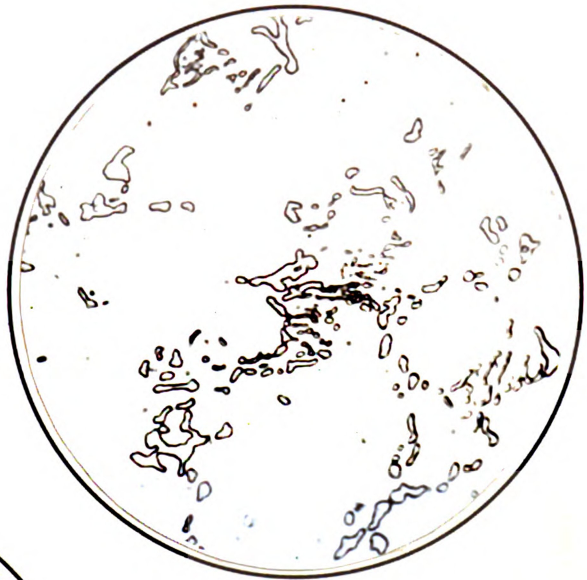
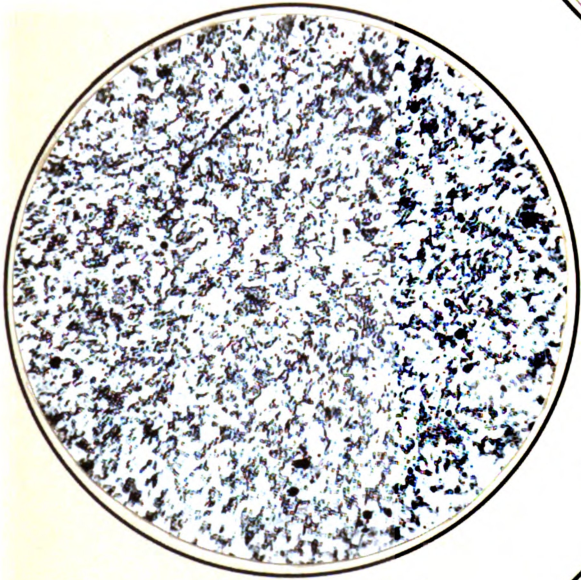


Figure 18 Specimen 7
1045 Steel Cooled through
lower critical for 204
minutes. Picral etch.



800x



100x

2000x

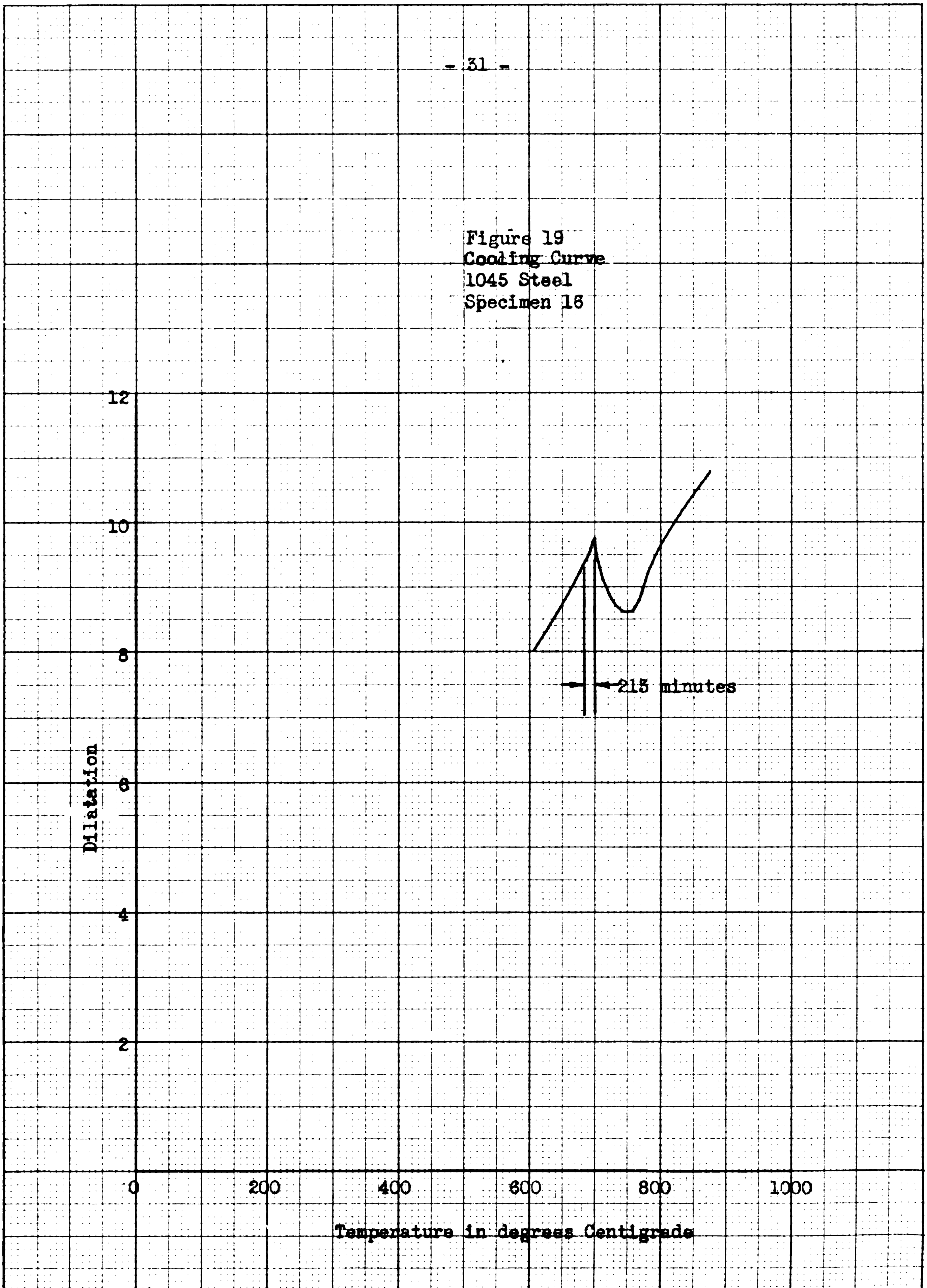
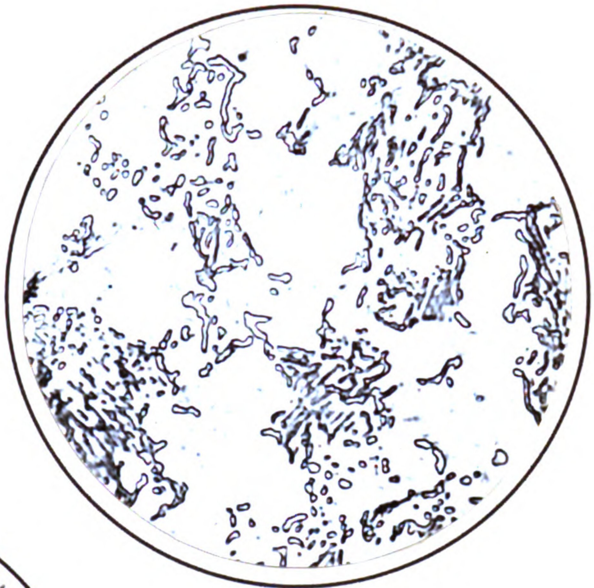
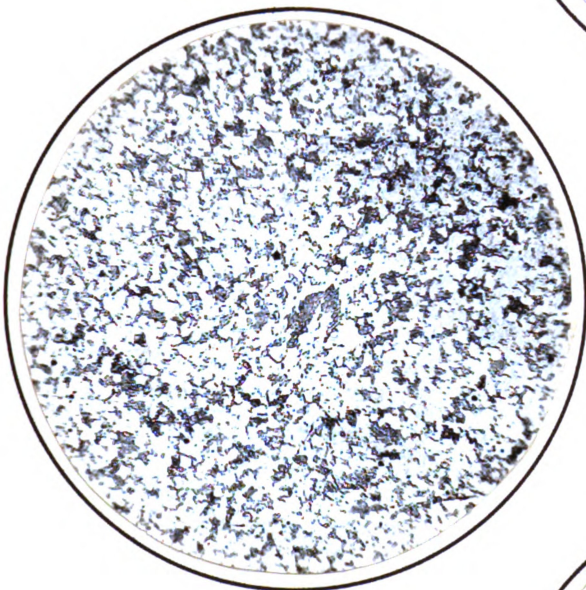


Figure 19
Cooling Curve
1045 Steel
Specimen 16
12
10
8
6
4
2
0
200
400
600
800
1000
215 minutes
Dilatation
Temperature in degrees Centigrade

Figure 20 Specimen 16
1045 Steel Cooled through
lower critical for 213
minutes. Picral etch



800x



100x

2000x

more, equilibrium would be reached. In normal cools, such as 1 or 2 minutes, equilibrium can be reached between pearlite and ferrite, as is shown in figures 6 and 10. However, in a very long cool there is no transformation to anything that looks like pearlite; but rather from the microstructure, there appears to be an aggregate of cementite in a matrix of ferrite. This is not in accord with the iron-carbon equilibrium diagram, but in repeated instances does appear to be the case. The idea that cementite separates out in a matrix of ferrite when very slowly cooled has been brought out by Publow and Heath in a discussion on the microstructure of pearlite.[7] The photomicrographs shown in this paper support this theory.

The iron-carbon equilibrium diagram is usually considered as an equilibrium diagram, but to quote Epstein "... the iron-iron carbide diagram can be regarded as though it were an equilibrium diagram, although in reality it is probably only a behavior diagram. As long as it is recognized as a behavior diagram no harm can be done."[2]

The transformation of austenite of a plain carbon steel has been observed. Since austenite has been defined as a solid solution of gamma iron with carbon and other elements, let us now consider other steels to see what the effect of the other elements might be.

Figure 21 is a photomicrograph of an S. A. E. 2340 specimen as received. The structure is different from any normal plain carbon steel. No attempt will be made to explain the structure except to say that the strange form must be due to elements other

Figure 21 As received
2340 Steel Picral etch.
600x

other than carbon.

Figure 22 is a dilatation curve taken on an S. A. E. 2340 steel. It must be noted that the critical points on cooling are much lower than for a plain carbon steel. Since any equilibrium diagram for this steel must be at least a three dimensional diagram the exact critical temperature could not be easily determined from a diagram. The dilatometer offers a good way to make the determination so that the steel may be worked on a commercial basis.

Rosenholtz and Oesterle say "...nickel lowers the critical points to such an extent that when 24 per cent of the element is present the critical points are depressed below room temperature."[6] According to Bain[1] nickel in steel is largely dissolved in ferrite, and at room temperature is in a solid solution with alpha iron. These points bring out the fact that in a nickel steel such as 2340, there are two phases at room temperature, ferrite and eutectoid. I did not say pearlite because the eutectoid is not made up of alternate lamallae of ferrite and cementite. Manganese in steel is carbide forming.[1] Because of this the eutectoid is made up of ferrite and carbide with the the carbide being both Fe_3C and Mn_3C, or some other form of manganese carbide.

Specimen 2 took 1 minute to go through the lower critical range, as is shown by figure 22. Figure 23 shows photomicrographs of specimen 2. It is noticed that the size of the grains, as shown at 100 diameters, is less than for a plain carbon steel. Nickel, and most other alloying elements, cause small grain size, which is a desired property.[6] At 2000 magnification a general spheroidization of the

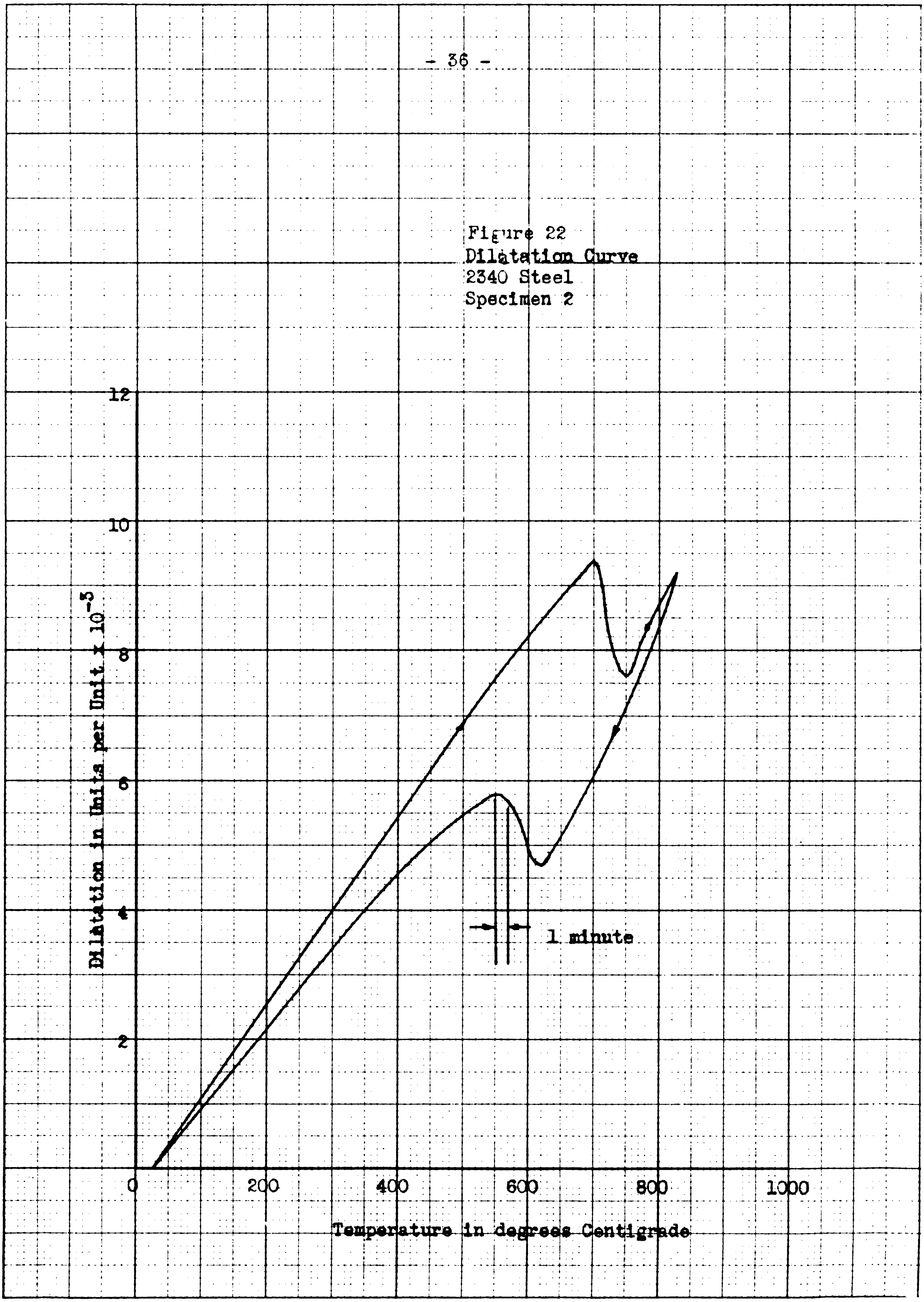
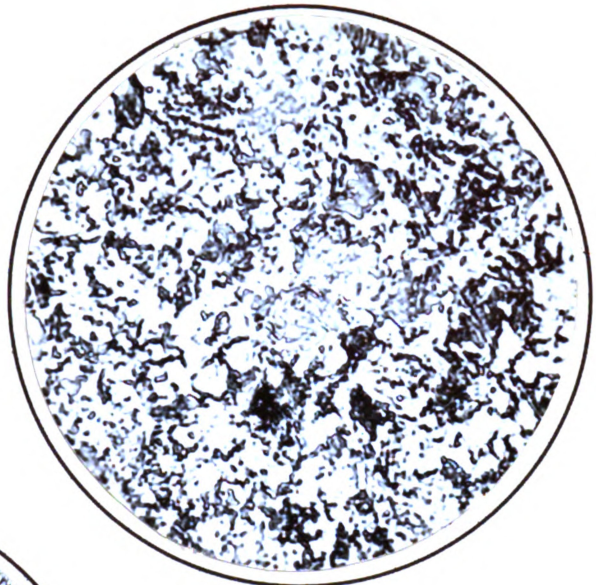
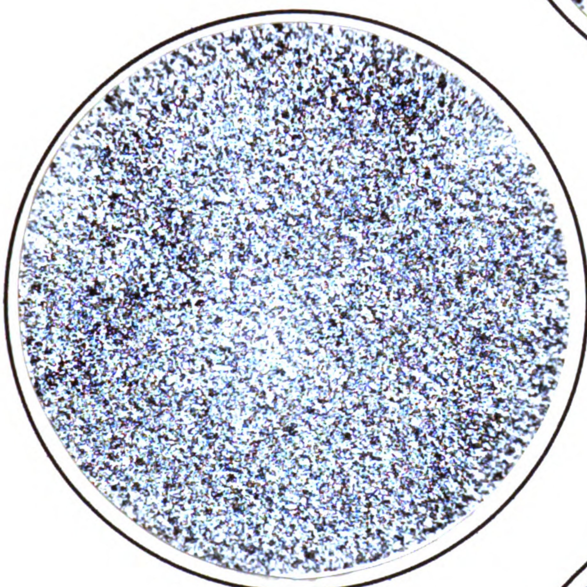


Figure 22
Dilatation Curve
2340 Steel
Specimen 2
12
10
8
6
4
2
0
200
400
600
800
1000
Dilatation in Units per Unit x 10^-5
Temperature in degrees Centigrade
1 minute

Figure 23 Specimen 2
2340 Steel Cooled through
lower critical for 1
minute. Picral etch.



800x



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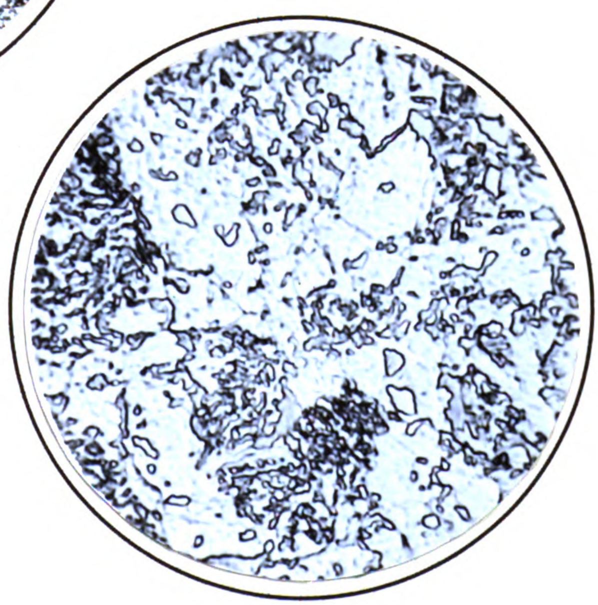


2000x

carbide is noticed.

Specimen 4 was cooled for 60 minutes through the lower critical range, as shown by figure 24. Figure 25 shows photomicrographs of specimen 4. Spheroidization seems to be more complete with longer cooling.

Specimen 9 was cooled for 282 minutes and appears to be even more spheroidized. (shown by figures 26 and 27) Specimen 10 cooled for 240 minutes checks the determination on specimen 9. These specimens could be called completely spheroidized, as the carbide is in spheroidized form and in equilibrium with ferrite.

The 2340 steel investigated contained 3.42% nickel and 0.71% manganese. The special steel contained 1.02% manganese, .62% chromium, and less than .1% of nickel. A dilatation curve on the special steel is shown in figure 30. The manganese does not lower the critical as much as the nickel in 2340 steel, and the microstructure is entirely different. (figure 31) Manganese, chromium and molybdenum are all carbide formers and manganese is very soluble in gamma iron.[1] Chromium is only partly soluble in gamma iron, but very soluble in alpha iron. Molybdenum is soluble in alpha iron, but nearly insoluble in gamma iron. There is only .24% molybdenum present in this steel, but this is an appreciable amount. The carbide formed in the special steel might therefore be called a manganiferrous cementite. This cementite would have to form in a similar manner to ordinary cementite, and would transform from austenite at the lower critical temperature.

The photomicrographs in figure 31 show specimen 1s after its 1 minute cool. This structure differs from that of a plain carbon

Figure 24
Cooling Curve
2340 Steel
Specimen 4

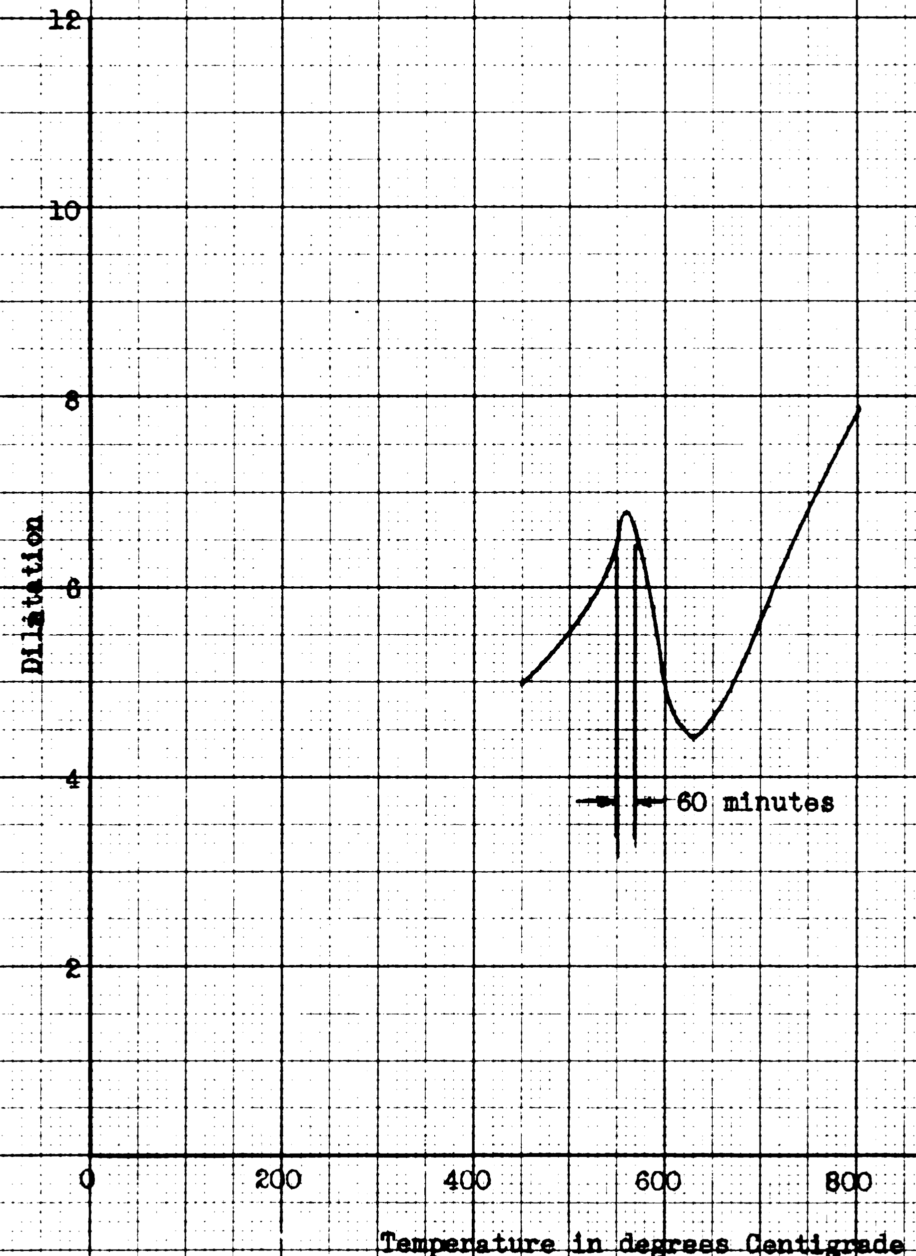
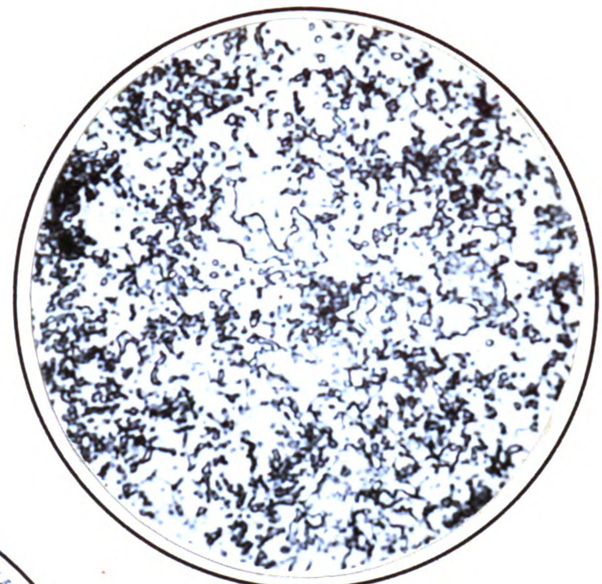
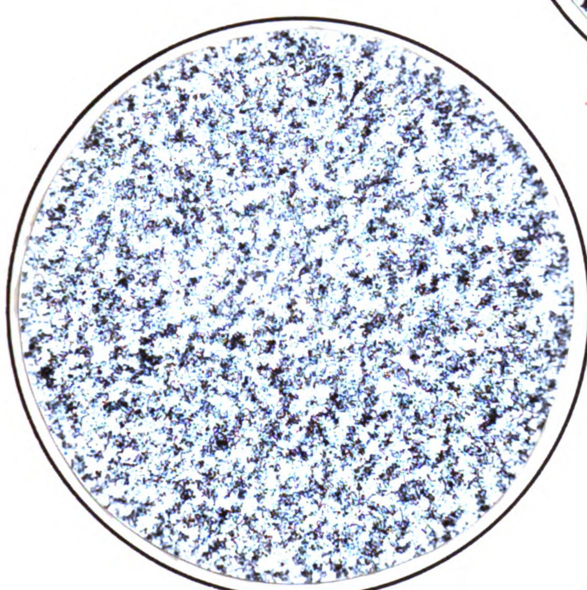


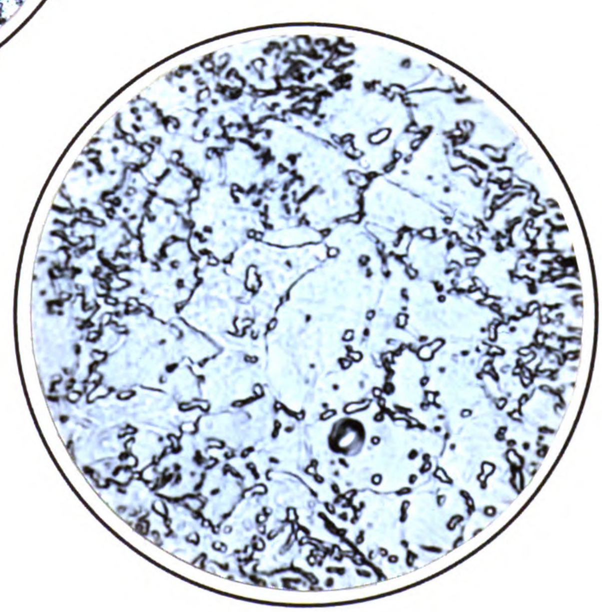
Figure 25 Specimen 4
2340 Steel Cooled through
lower critical for 60
minutes. Picral etch.



800x



100x



2000x

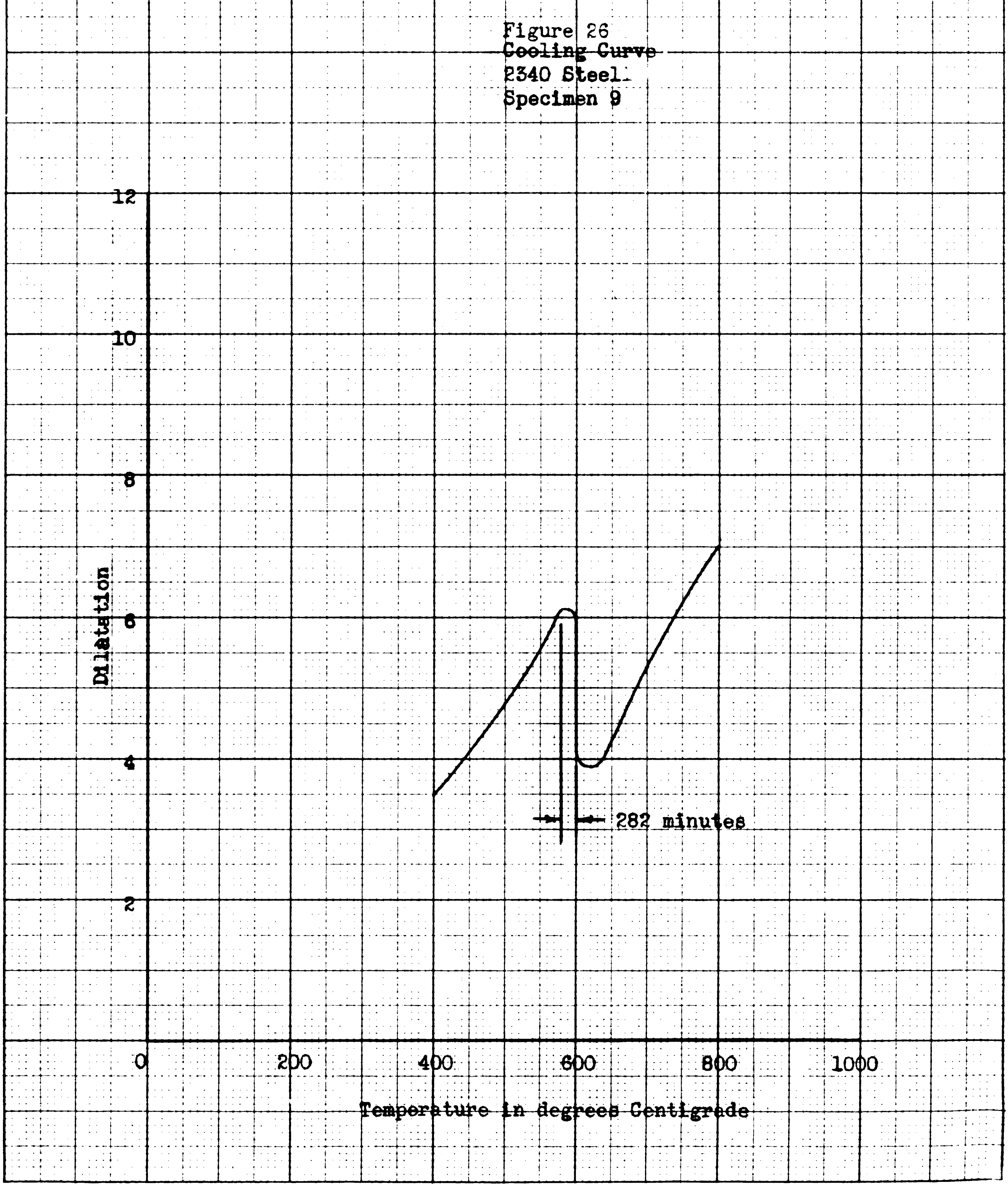
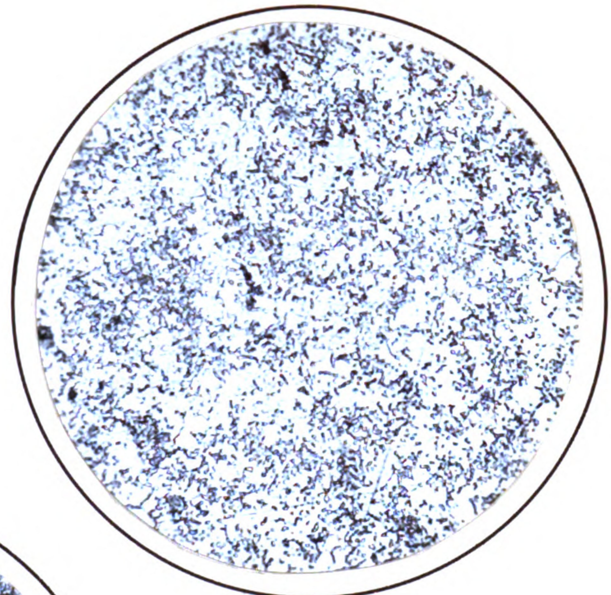
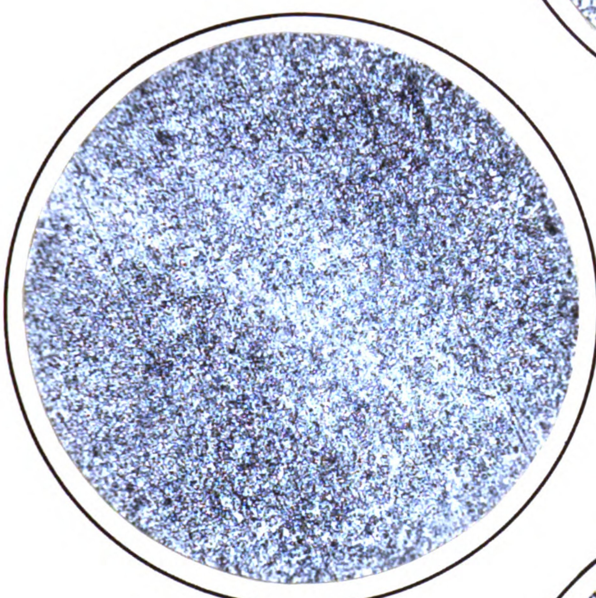


Figure 26
Cooling Curve
2340 Steel
Specimen 9
12
10
8
6
4
2
Dilatation
282 minutes
0
200
400
600
800
1000
Temperature in degrees Centigrade

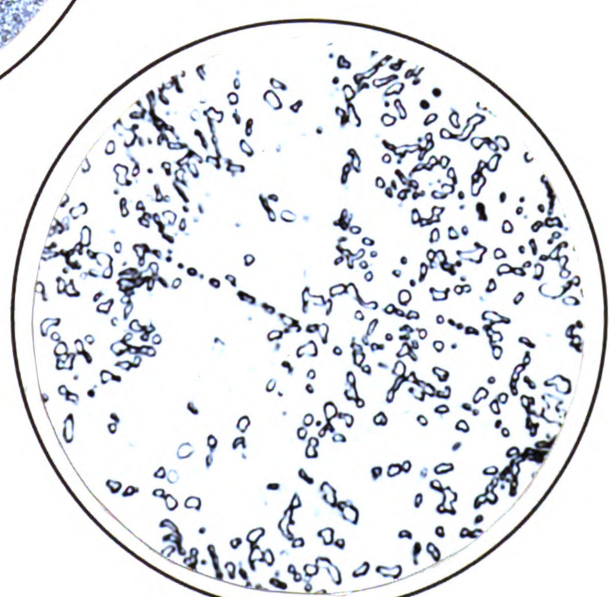
Figure 27 Specimen 9
2340 Steel Cooled through
lower critical for 282
minutes. Picral etch.



800x



100x



2000x

Figure 28
Cooling Curve
2340 Steel
Specimen 10

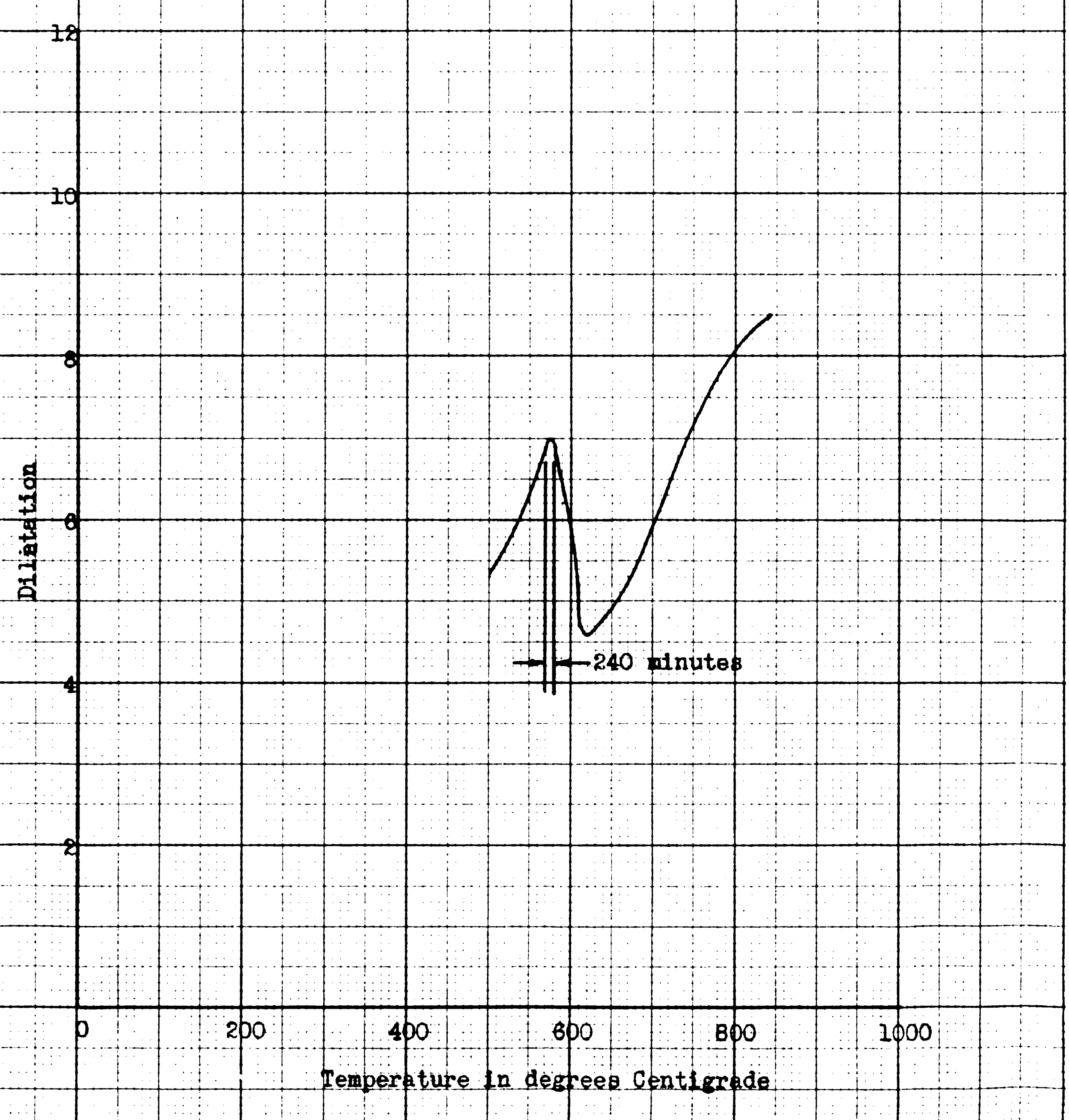
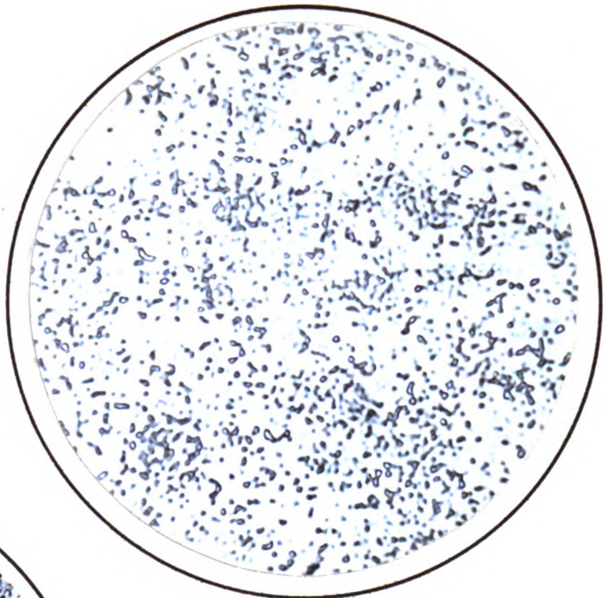
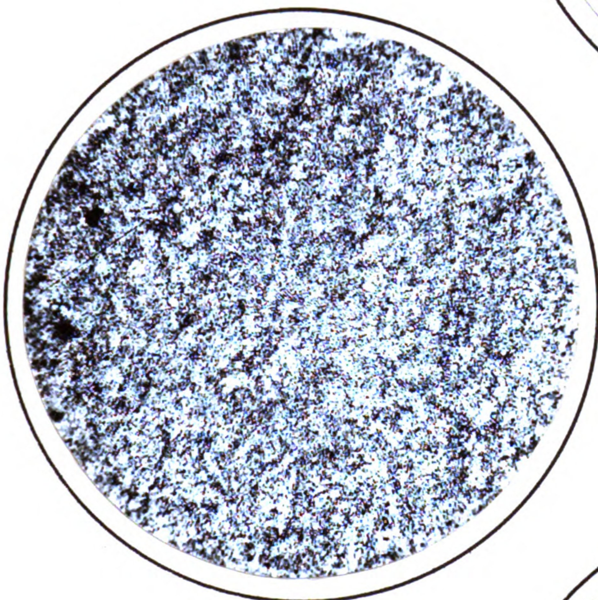


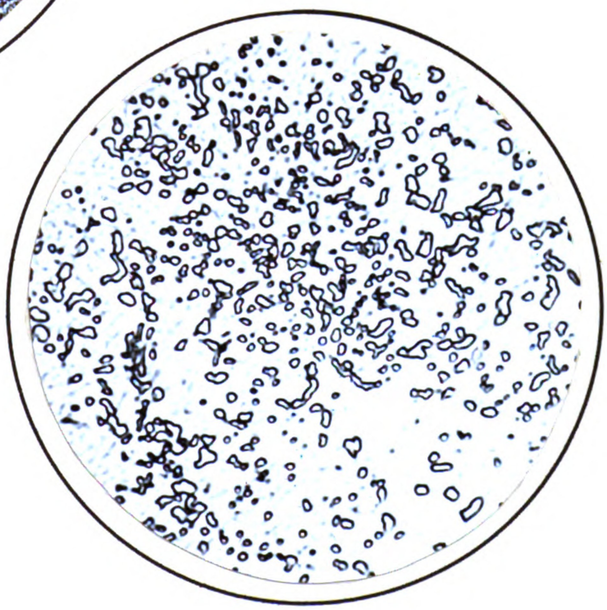
Figure 29 Specimen 10
2340 Steel Cooled through
lower critical for 240
minutes. Picral etch.



800x



100x



2000x

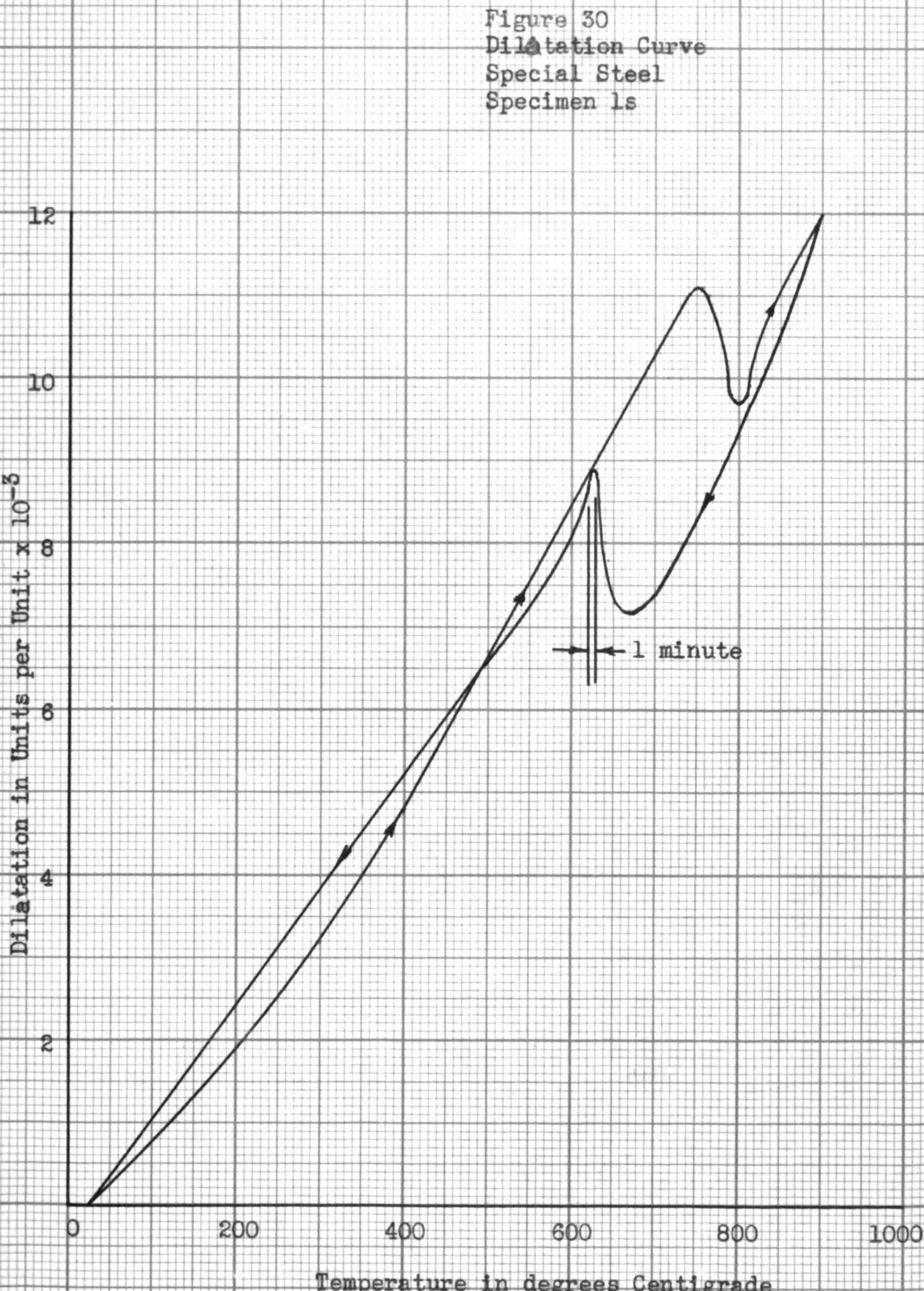
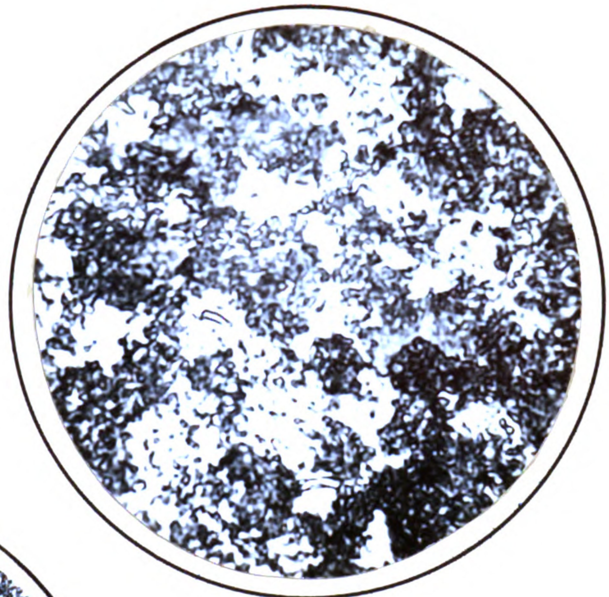
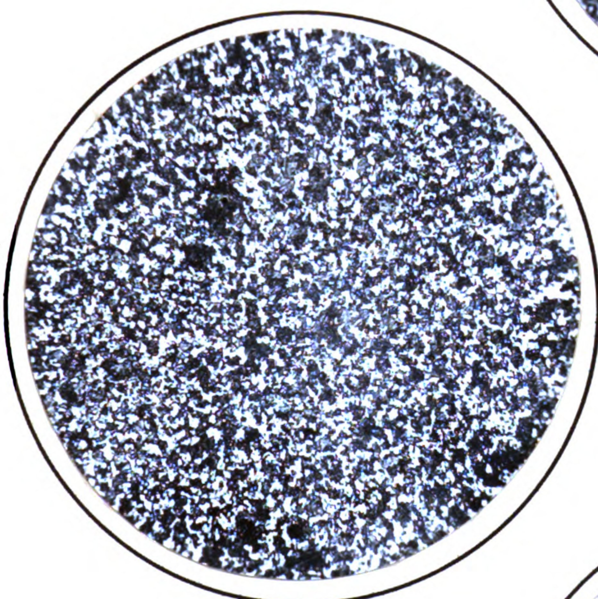


Figure 30
Dilatation Curve
Special Steel
Specimen ls
12
10
8
6
4
2
0
200
400
600
800
1000
1 minute
Dilatation in Units per Unit x 10^{-3}
Temperature in degrees Centigrade

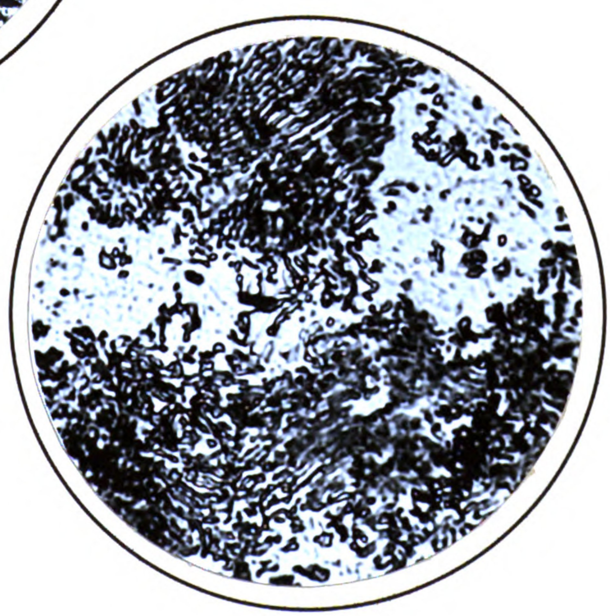
Figure 31 Specimen 1s
Special Steel Cooled through
lower critical for 1
minute. Picral etch.



800x



100x



2000x

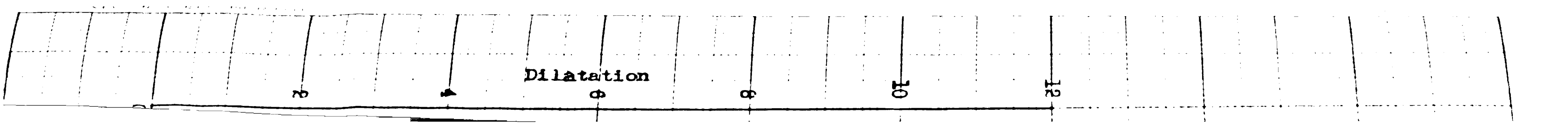
steel in two specific ways.

First the eutectoid constituent is not clear-cut and sharply defined, as it is in the plain carbon steel. The polishing of this steel offers many problems that are peculiar to steels containing manganese. If just ordinary care is used in the polishing and etching it is practically impossible to get true separation of the eutectoid, or to show its detail. Only after repeated attempts at this polishing and etching can the true structure be brought out. The eutectoid can not be the same thing as that contained in a plain carbon steel as it behaves so very differently. It has a strong tendancy to smear, and behaves as if it were very soft and ductile.

The second difference is that there appears to be more eutectoid present with the same carbon content. This has been brought out by Publow and McGrady.[5] They have shown that the presence of manganese shifts the eutectoid point very sharply to the left. This is readily observed in the photomicrographs in this paper.

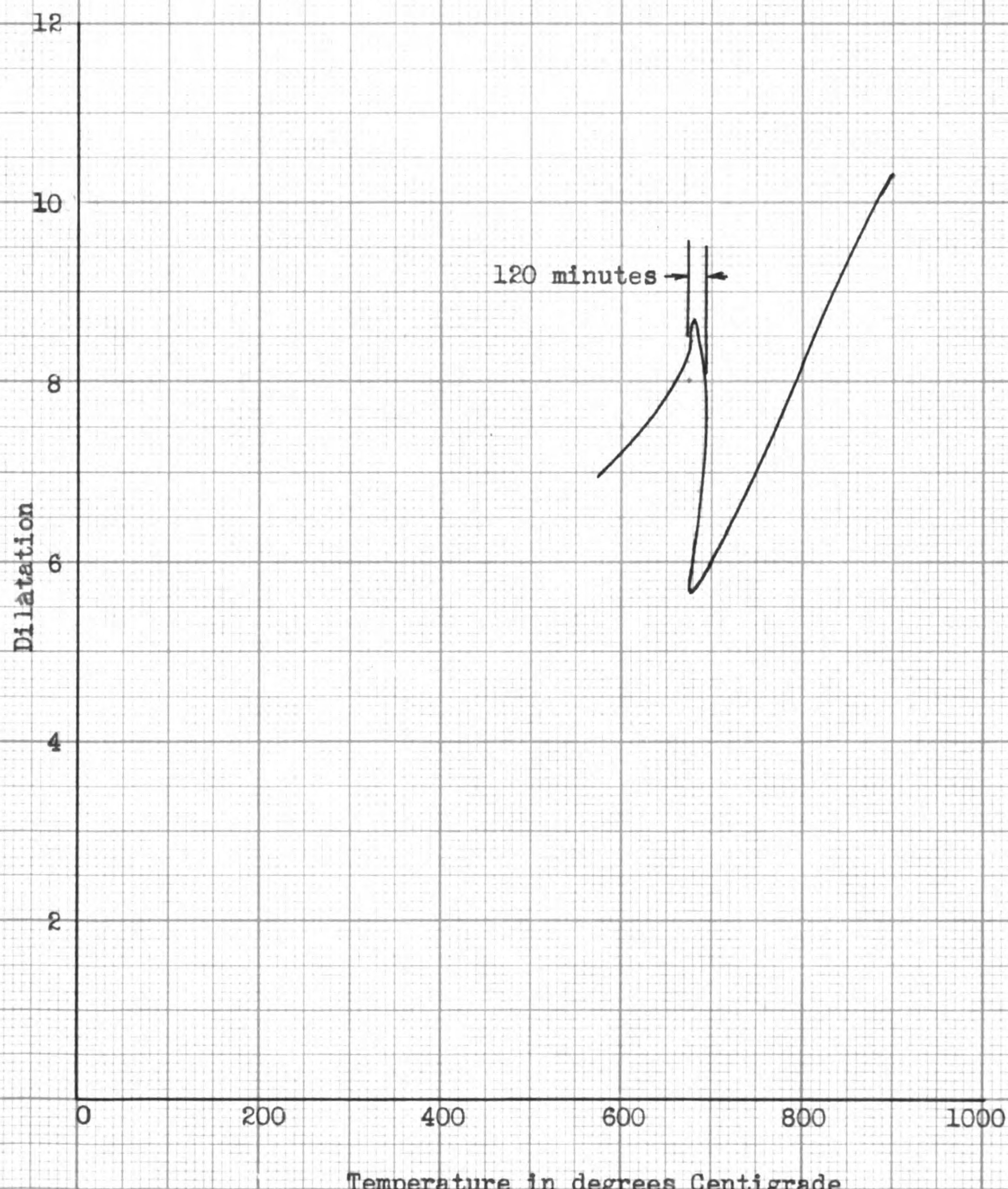
In an attempt to run a slow cool on the special steel some difference in behavior was noted. When the specimen was in the range between the upper and lower critical temperatures, and the temperature was held constant, the specimen would still transform with a gradual rise in temperature due to the evolution of heat. This transformation was found to take place at a much higher temperature than would be expected.

Figure 32 is a contraction-temperature curve on specimen 2s. 120 minutes were required for the transformation to take place. The photomicrographs are shown in figure 33. It is noted that the temperature



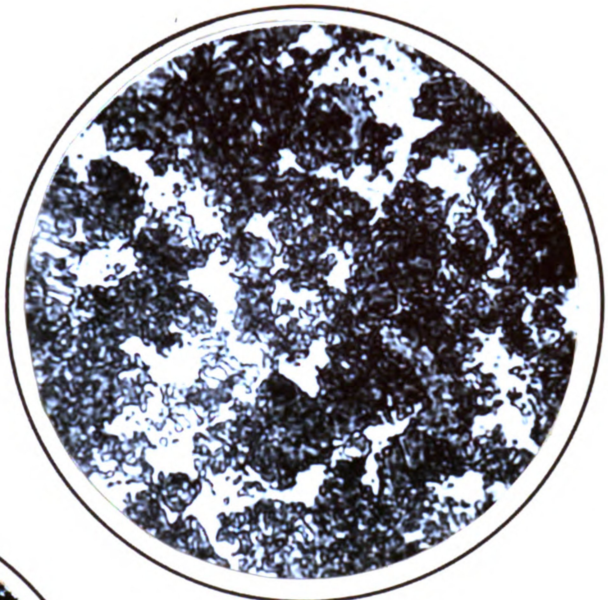
Dilatation
2
4
6
8
10
12

Figure 32
Cooling Curve
Special Steel
Specimen 2s

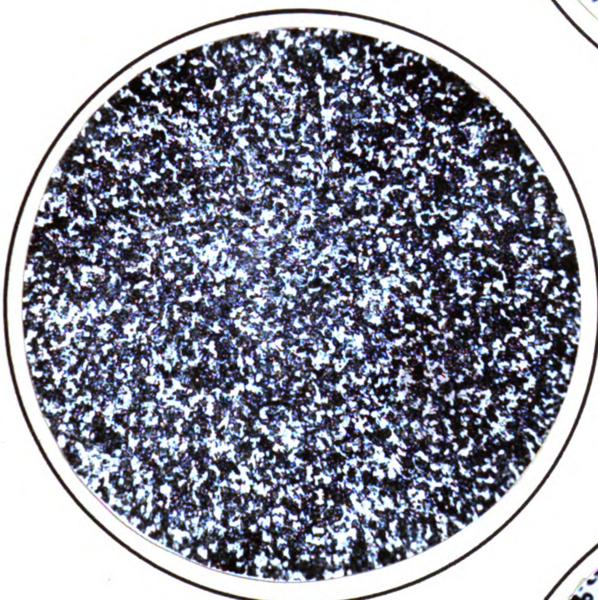


Figu
Spec
lowe
min

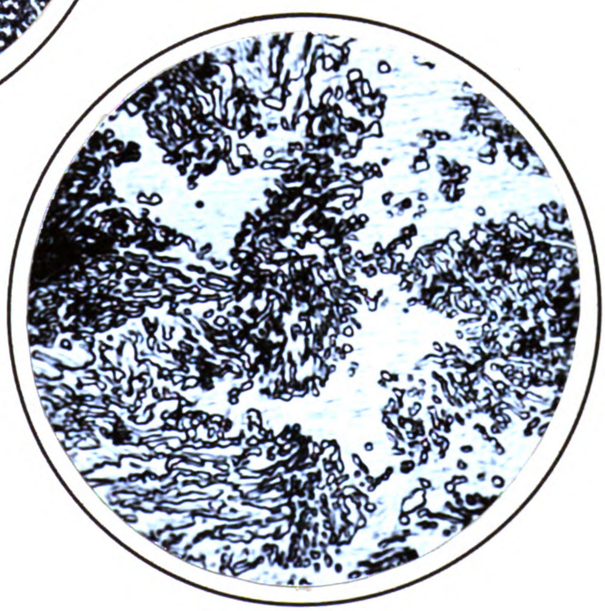
Figure 33. Specimen 2s Special Steel Cooled through lower critical for 120 minutes. Picral etch.



800x



100x



2000x

went up, but still the tranformation occurred, and that it was complete at a higher temperature than that at which it started. After repeated attempts this was found to be the slowest transformation that was possible to have with the dilatometer. This can be probably expìained by the presence of chromium and molybdenum. Rosenholtz and Oesterle show that chromium and molybdenum both cause a harder steel because the effect of these elements is to cause a rapid transformation from austenite. [6]

In the case of the special steel the eutectoid resulting from the transformation of austenite is probably a complex carbide formed from the manganese and the iron. From the solubility of chromium and molybdenum in alpha iron it would seem that they would be present in the alpha iron constituent, and not in the eutectoid to be observed by the microscope.

The form of the eutectoid in the special steel appears to be lamellar with a few spheroidal particles. If the specimen could be cooled slower equilibrium could probably be reached between the carbide and the ferrite. There must be some other means of slow cooling before a definite spheroidal structure can be seen because in the dilatometer the critical occurs at a temperature very little below the A_{r3} temperature, and it is very difficult to slow down the reaction.

Summary

The ultimate product of the slow decomposition of austenite in a plain carbon steel is probably spheroidal cementite in a matrix of ferrite. This is indicated by the photomicrographs shown in this paper. Another form of spheroids should not be confused with the form caused by slow cooling. A quenched specimen may be spherodized by heating to a temperature below the lower critical. Figure 34 shows two photomicrographs of this type of spheroids. This appears to be an entirely different structure than spheroidal cementite resulting from the slow transformation of austenite.

Nickel causes a great lowering of the critical temperature and overbalances the effect of manganese which forms a eutectoid that does not appear to be clear-cut. Nickel is present in the ferrite and manganese is a carbide former.

The ultimate product of decomposition of austenite of an S. A. E. 2340 steel is probably spheroidal carbide in equilibrium with ferrite. In no instances was a lamellar structure observed in this steel.

The ultimate product of decomposition of austenite of the special steel studied might be spheroidal carbide in equilibrium with ferrite. The effect of chromium and molybdenum, which are probably present in the ferrite, seems to be the acceleration of the transformation of austenite to its constituents.

S. A. E. 1045

Figure 34 Quenched in water from 850 degrees centigrade and spherodized at 550 degrees.
600x Picral etch.

S. A. E. 2340

Suggestions for Further Work

A complete study of the slow decomposition of austenite made from plain carbon steels ranging in carbon content from 0.2% to 1.2% would undoubtedly show differences of decomposition depending on the carbon content.

An investigation of nickel steel containing no appreciable amount of manganese or other elements. In such a steel as this the effects could be traced directly to the nickel. Such a steel would probably not be available as a commercial steel, but could be specially made.

A study of the effects of other elements such as manganese, chromium and molybdenum. These steels would also have to be specially made.

A method of preparing specimens for microscopic examination that will not cause special effects such as those brought about by polishing.

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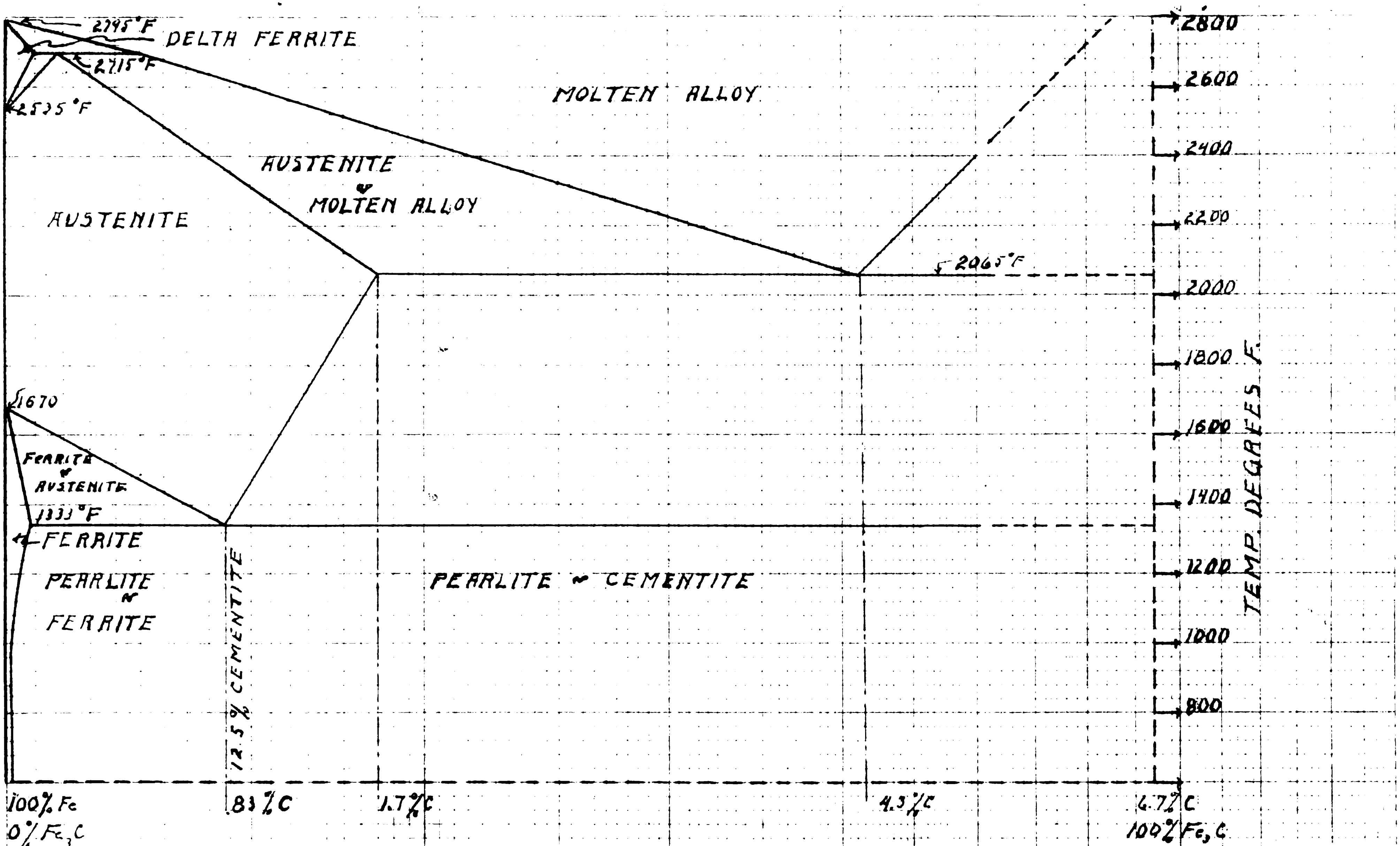

IRON, IRON-CARBIDE EQUILIBRIUM DIAGRAM