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AN ISOTHERMAL STUDY OF BAINITIC AND MARTENSITIC TRANSFORMATIONS IN SOME LOW ALLOY STEELS USING A NEW MAGNETIC PERMEABILITY TECHNIQUE

Clyde Ernest Ericsson
(M.S. thesis)

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AN ISOTHERMAL STUDY OF BAINITIC AND MARTENSITIC TRANSFORMATIONS IN SOME LOW ALLOY STEELS USING A NEW MAGNETIC PERMEABILITY TECHNIQUE

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ABSTRACT

The upper and lower bainitic hardenabilities have been established for the commercial low alloy heat treatable steels AISI 4130, AISI 4140, D6AC and AMS 6416 (300-M). The kinetics of the bainitic reaction below the martensite start temperature (M_s) have been studied and the martensite range temperatures have been determined. The materials AISI 4130 and 300-M were austenitized at both 880°C and 1200°C and the effect of the austenitizing temperature on the upper bainitic hardenability was determined. A magnetic permeability technique was employed in this investigation to monitor the austenite transformations. Computational methods were developed to decode, analyse and plot the austenite decomposition data.

I. INTRODUCTION

The microstructure-toughness relationship in low alloy ultra high strength steels has received increasing attention in recent years. This interest has stemmed from the manner in which the toughness of the steels has been found to vary with increasing strength levels. The change in toughness has not been predictable from steel to steel and has appeared to be contingent upon the microstructure of each alloy.

The alloys studied in the investigation were AISI 4130, AISI 4140, D6AC and AMS 6416 (300-M). These alloys are referred to as tempered martensitic steels. Conventionally, steels are considered to be of the tempered martensitic type if they have good pearlitic hardenability and can be quenched to a fully martensitic structure.

Some tempered martensitic steels have good pearlitic hardenability without good bainitic hardenability. In these steels, significant amounts of proeutectoid ferrite, upper bainite and lower bainite may form during quenching. Small amounts of either proeutectoid ferrite or upper bainite have been shown to have detrimental effects on the fracture toughness.[1] Lower bainite is considered to be comparable to tempered martensite in fracture toughness.[2,3] Therefore, it appears essential to know the upper bainitic hardenability of tempered martensitic alloys as well as their pearlitic hardenability.

The primary objective of this investigation was to re-examine the upper and lower bainitic hardenabilities of four widely used tempered martensitic steels (the pearlitic hardenabilities of these steels are well known). This was to be accomplished by utilizing a new sensitive magnetic permeability method to follow the austenite decomposition.

The original method of following phase transformations in steels was developed by Bain and Davenport in 1930. This involved very laborious metallographic examinations of a series of specimens that had been transformed for various periods of time at each of a number of temperatures. Although this method was widely used, it was very time consuming and it was limited by poor accuracy and consistency.[4]

Other investigators have followed the phase transformation by monitoring the change in a physical property during the transformation. The methods used have involved measuring changes in electrical resistance,[5] physical dimensions,[6] hardness,[7] or a magnetic property.[8,9] Most of these techniques have been subject to criticism. For example, the electrical resistivity change is not only a function of the transformation, but it is also a function of particle size and lattice coherency.[4] The measurement of dilation is subject to a similar criticism when the reference specimen is a long, thin rod and the transformation product has an acicular structure like that of bainite.[10]

There were three secondary objectives of the present investigation. One of these was to examine the kinetics of the bainitic reaction below the M_s. If the bainite reaction could be distinguished from the martensite reaction at temperatures below M_s, then the values of M_{50} and M_{90} could be determined experimentally.

Another objective was to examine the effect of the austenitizing temperature on the upper bainitic hardenability. A recent investigation has shown that the fracture toughness of 4130, 4140 and 300-M increased with an increase in the austenitizing temperature.[3,11] Therefore, to determine if this enhancement of toughness was related to a change in the

upper bainitic hardenability, specimens of 4130 and 300-M were austenitized at both 800°C and 1200°C.

The final secondary objective was to check the validity of the isothermal diagrams of the recently developed alloys, D6AC and 300-M. Most sources of isothermal transformation data do not include time-temperature-transformation (TTT) diagrams for these alloys, and it seemed advisable to check the accuracy of the diagrams in the literature.

II. EXPERIMENTAL PROCEDURE

A. Material Preparation

The materials used in this investigation were commercial low alloy heat treatable steels. They were received as 5/8 in. thick bar stock in the fully annealed condition. Table I lists the chemical compositions of these alloys. Specimens for isothermal treatments were prepared by cutting 0.05 in. thick strips from the bar stock and then cold rolling the strips to thicknesses of either 0.03 in. or 0.02 in. The specimens were then sheared to the final dimensions of 2.5 in. by 0.56 in. by the appropriate thickness.

B. Magnetometric Technique and Apparatus

The austenite transformations in each steel were studied by employing a magnetic permeability method (MPM) which was recently developed.[12] The MPM permitted rapid and sensitive measurements of the rate of austenite decomposition as materials transformed isothermally.

The MPM principally consisted of quenching a specimen from an austenitizing temperature into a temperature controlled isothermal bath, where the specimen was held within the field of an inductor coil, through which a one kHz current flowed. As the austenite decomposed, the increase in magnetic permeability increased the inductance of the coil. The change of inductance resulted in a change of period of an oscillator circuit. By continuously recording the period, the decomposition of the austenite could be conveniently followed. Figure 1 provides a schematic drawing of the apparatus. Figure 2 displays the block diagram of the electronic system.

The actual experimental procedure consisted of the following steps:

1. The electronic system was turned on and allowed to stabilize.
2. The specimen was attached with tantalum wire (non-magnetic) to the end of a Hastelloy rod, which passed through a water cooled vacuum seal at the top of the furnace.
3. The specimen was positioned in the cold zone of the furnace and the bottom lid of the furnace was closed.
4. The furnace was evacuated by a pumping system which included a mechanical pump, a diffusion pump and a liquid nitrogen cold trap.
5. The quenching medium was circulated in a counter-current, turbulent manner and allowed to stabilize at the desired temperature.
6. After obtaining a vacuum of 8×10^{-5} Torr or better, the specimen was raised into the hot zone and austenitized for 15 minutes.
7. After the 15 minute period the tube furnace was isolated from the evacuation system and the latch holding the bottom lid of the furnace was released.
8. The paper tape punch was turned on at a rate which recorded the period of oscillation at intervals of 0.77 seconds.
9. Argon gas was released into the tube furnace to force the bottom lid open.
10. The Hastelloy rod was then immediately thrust downward placing the specimen simultaneously into the circulating quench medium and within the field of the inductor coil. (This motion of the Hastelloy rod also activated a switch which converted the first digit from an even to an odd value in the coded six digit output. Only the last five digits were used to measure the period.)

11. The interval of recording the period was increased to 7.7 seconds as the rate of transformation decreased. As the rate of transformation decreased even further the recording interval was increased to 77.0 seconds. (These interval changes were denoted by changing the value of the first digit in the coded output.)

Two austenitizing temperatures were used in this investigation. The materials 4130, 4140, D6AC and 300-M were austenitized at the conventional heat treating temperature, 880°C. Studies were also made on 4130 and 300-M austenitized at 1200°C. In conjunction with this change in temperature the thickness of the specimen was also altered. At the lower austenitizing temperature a 0.02 in. thick specimen was used, and at the higher temperature a 0.03 in. thick specimen was used.

After austenitizing, the specimens were isothermally held in baths whose temperatures ranged from 25°C to 500°C. Well below the M_s, specimens were transformed at temperature intervals of 50°C. Upon approaching the M_s, and at temperatures above the M_s, specimens were transformed at smaller temperature intervals.

Different quenching medias were used, depending upon the temperature at which the specimens were to be isothermally transformed. For temperatures between 25°C and 100°C a quenching oil was used. Between 150°C and 200°C a tempering oil was substituted. When temperatures greater than 200°C were needed, a low temperature nitrate-nitrite salt was used.

C. Cooling Rate Determination

The procedure for determining the combined cooling rate of the apparatus and material was as follows:

1. Specimens of 4140 were prepared with dimensions of 2.5 in. by 0.56 in. by 0.02 in. and 2.5 in. by 0.56 in. by 0.03 in.
2. Thermocouple leads were cold rolled to 3 mils or less and then spot-welded to the opposite surfaces of the specimens.
3. The specimens were austenitized in vacuum according to the aforementioned procedure.
4. The austenitized specimens were dropped directly into the quenching medium. The cooling rates were followed with a high-speed recorder at a graph rate of 3 in. per second. Table II lists the cooling rates as a function of quenching medium temperature and specimen thickness.

D. Temperature-Structure Calibration

Calibration for the composite effect of temperature and structure on the magnetic permeability of the material was performed using 0.02 in. thick specimens. For temperatures below M_s, the calibration for 4140, 4130, D6AC and 300-M consisted of quenching an austenitized specimen into oil at room temperature. The 100% martensite specimen was then held briefly at various temperatures below the M_s to note the change in period. At temperatures greater than M_s, the temperature at which the reference structure was transformed depended on the specific material.

Specimens of 4140 were completely transformed isothermally at 325°C and 450°C. For temperatures between the M_s and 400°C, the 325°C specimen was used as a reference for calibration. The 450°C specimen

was used as a reference for calibration above 400°C. The calibration curve of 4140 is given in Fig. 3.

Specimens of 4130 were isothermally transformed to completion at 375°C and 450°C. The 375°C specimen was used for calibration purposes at temperatures above the M_s and up to 425°C, the 450°C specimen was used at temperatures from 450°C to 500°C. The calibration curve of 4130 is shown in Fig. 4.

A specimen of D6AC that was completely transformed at 300°C was used as a reference for temperatures greater than the M_s. The calibration curve of D6AC is given in Fig. 5.

The reference specimen for 300-M was an austenitized specimen that was quenched to room temperature and then held at 300°C for one hour. Above 350°C the curve was extended to be equivalent to the temperature-structure calibration curve of an AISI 4340 steel.[12] The calibration curve of 300-M is given in Fig. 6. (The reason for this is discussed in detail later.)

E. Volume Fraction Transformed Calibration

The non-linearity of the change in period (ΔP) with the amount of volume fraction transformed was determined by quenching specimens of different thicknesses to room temperature. By maintaining the other dimensions constant, the change in thickness of the specimens could be correlated to their change in weight and in turn, the volume fraction transformed. For example, the strength of the signal of a 2 gm specimen that is 100% transformed is equivalent to a 4 gm specimen which is 50% transformed. The ΔP was measured for each specimen having a thickness of 0.03, 0.02, 0.0.5, 0.010 and 0.005 in. The corresponding dependence of ΔP with weight is shown in Fig. 7.

F. Computer Analysis

A computer program was written which did the following:

1. Decoded the paper tape output.
2. Corrected for the non-linearity of the change in ΔP vs volume fraction transformed.
3. Converted the corrected change in ΔP to absolute volume fractions.
4. Plotted the kinetics of transformation of the isothermal curves.
5. Plotted the initial TTT diagrams.

A listing of the computer program is given in the Appendix.

G. Metallography

Specimens for optical metallography were sectioned, mounted in Koldmount and abraded on successively finer silicon carbide papers to 600 grit. The specimens were than polished with 1 micron diamond paste and finally micropolished in a solution of distilled water and 0.05 micron alumina. The specimens were etched with 1% or 2% nital for 5-30 seconds.

III. RESULTS AND DISCUSSION

A. Magnetometric Technique

The magnetic permeability method permitted continuous measurements to be made of the fraction of austenite decomposed as the alloys were isothermally transformed. To determine the identity of the decomposition products, it was necessary to observe the kinetics of the transformation, and subsequently to correlate the kinetics with the microstructure.

At the isothermal holding temperature of 25°C, each of the four steels exhibited a transformation which stabilized at virtually 100% transformed within the initial four seconds--specimens reached 25°C within 2 seconds after immersion in the quenching medium. This instantaneous transformation was recognized as an athermal martensitic phase transformation. As the isothermal holding temperature was increased, the shape of the transformation-time curves began to change. Less transformation occurred instantaneously, and the amount that transformed isothermally increased with time. The fraction transforming athermally (to martensite) decreased with increasing transformation temperature. The isothermal fraction transformed was regarded as bainitic, which is classified as a time dependent transformation.[13]

With a continued increase in isothermal holding temperature, a temperature was reached at which only one percent of the austenite was instantaneously decomposed. According to definition, this temperature is identified as the M_s temperature. Further increases in the isothermal holding temperature eliminated the athermal transformation.

At transformation temperatures above M_s, a limitation of the MPM was encountered. The difficulty involved resolving two time dependent

transformations which occurred simultaneously, such as mixtures of upper bainite with lower bainite, or upper bainite with proeutecoid ferrite. However, by plotting a series of isothermal transformation curves, the upper and lower bainite ranges could be determined when their individual "activation energies" resulted in different incubation periods for nucleation. Microscopic methods usually had to be employed for positive identification of mixtures of decomposition products.

Two methods are currently employed to determine the temperatures at which the values from M_s through M_{90} occur. One method requires that the M_s be determined by metallography. Then emperical equations are used to determine the temperatures for the other levels of martensite transformation.[14] The second method is known as the quench-temper technique, which was developed by Greninger and Troiano.[15] This method involves quenching austenitized specimens to various temperatures, holding for a short period of time, then up-quenching to temper the martensite, followed by quenching to transform the remaining austenite to martensite. This technique is limited to steels with high bainitic hardenability because martensite has a nucleating effect on the formation of bainite, and also because the bainite has an appearance similar to that of tempered martensite.[16] Both of these methods have been criticized for the indirect manner in which they attempted to attain the martensite range temperatures.

The MPM provides a direct experimental means for determining the M_s through M_{90} temperatures. A brief examination of the kinetics of transformation curves given in Figs. 8-19 vividly depict the percentages of martensite that were transformed athermally at a given temperature.

B. Cooling Rate Determination

In order to determine the validity of the MPM data as the elapsed time approached zero, it was necessary to measure the cooling rates of the specimens quenched to different temperatures. It was possible to monitor these cooling rates by spot-welding a thermocouple to the opposing surfaces of the specimen. The thickness of the specimen was also varied so the effect of the cooling rate with thickness could be observed.

The data given in Table II shows that the values of ΔP are valid after the initial 2 seconds. These results were obtained from specimens of 4140 but they also pertain to the materials 4130, D6AC and 300-M.

C. Temperature-Structure Calibration

The magnetic permeability of a material is a function of the temperature, strain, and morphology of the phases present.[17] Therefore, calibration curves were needed for each alloy to account for the magnitude of these effects.

The structure of the reference specimens for calibration was selected according to the temperature range that was to be calibrated. This eliminated the necessity of having to separate the individual effect of temperature and structure upon the permeability. For the temperature range below the M_s, a fully martensitic specimen was used. At temperatures above the M_s, a fully bainitic specimen was substituted. In both temperature ranges the specimens were held for a short period of time, and the slight tempering of the specimen that occurred was found to have very little effect on the permeability. These experimentally derived calibration curves for 4130, 4140, D6AC and 300-M are congruent

with that found for the general dependence of permeability with temperature.[18]

The method for determining the calibration curve at temperatures above M_s was modified for 300-M. Since the bainitic transformations did not go to completion, these specimens could not be used as a reference. Instead a martensitic structure was tempered for one hour at 300°C and was used to approximate a fully bainitic structure. This specimen was then used for calibration at 300°C and 350°C. The tempered martensitic standard was not used at temperatures greater than 350°C. Above this temperature, the calibration curve of an AISI 4340[12] steel was used. The 4340 and 300-M calibration curves could be expected to be virtually identical, since 300-M has a chemical composition similar to that of 4340.

D. Volume Fraction Transformed Calibration

The change of inductance with volume fraction transformed is shown in Fig. 7. The relationship is not linear. It obeys the quadratic equation $K = A(\Delta P)^2 + B(\Delta P) + C$. The constants A, B and C are equal to 6.9×10^{-7}, 1.3×10^{-3} and 1.58×10^{-1}, respectively.

E. Analysis of Data

The martensite range temperatures for most of the steels studied in this investigation have already been reported.[19,20,21] However, many of the values were not in accord with those determined by using the MPM. A comparison of these values is shown in Table III.

Generally the MPM values are lower than those previously reported. Several factors could account for these variations. First, the 4140 studied in this investigation has a significantly higher alloy content than the reference 4140. All of the common substitutional

alloying elements lower the M_s,[22] thus, the increased alloy content could have caused the decrease in the M_s. Second, these discrepancies could have arisen because of inaccuracies inherent in the conventional measurement techniques. Other investigators[23] have suggested that these techniques, as discussed on page 11, have the tendency to indicate M_s values that are higher than the actual values. Also, it has been shown that there should be approximately a 200°C difference between the M_s and M_{90} in low alloy steels.[14] These recent opinions favor the new values, which were determined with the MPM.

The M_s temperatures of both 4130 and 300-M increased when the austenitizing temperature was increased. This change in austenitizing treatment resulted in larger austenite grains, as shown in the comparison of Figs. 20 and 21 with Figs. 22 and 23. In a single phase grain growth reaction, it is expected that the enlarged grains are bound by lower energy boundaries.[24] Therefore, the presence of the lower energy grain boundaries requires a smaller thermal gradient for the occurrence of the martensitic shear transformation.

The recently published TTT diagrams of 4130, 4140, D6AC and 300-M have shown that the bainitic transformation in these alloys obeys C curve kinetics.[19-21] In this investigation an acceleration of the austenite decomposition was observed at temperatures just above the M_s. This decrease in incubation period for lower bainite was observed consistently in all six of the TTT diagrams, Figs. 24-29. S-shaped curves for the bainite reaction have also been observed by other investigators.[25,26,27]

Below the M_s the rapid decomposition of austenite continued for a few seconds beyond the time required for cooling. This behavior, which suggests the formation of martensite by both isothermal and athermal modes of transformation, has also been observed by Averbach and Cohen.[24]

The bainite transformation can be followed below the M_s by subtracting the martensitic transformation from the total amount of austenite decomposed. In this manner it can be shown that the lower bainite reaction is accelerated just below the M_s. This decrease in incubation period for the nucleation of bainite is associated with the increased number of nucleation sites which result from the presence of strained martensite-untransformed austenite interfaces. As the temperature is further decreased the diffusion rate decreases. Thus the growth rate is also decreased and the lower bainite transforms according to C curve kinetics.

In the previously published TTT diagrams of 4140 and 4130, the upper bainite - lower bainite transformation has been shown as a single smooth C curve.[19] From these diagrams it was not possible to determine the separate upper bainite and lower bainite hardenabilities. Using the MPM these hardenabilities could be determined and are shown in Figs. 24-26.

The hardenabilities of 4130 austenitized at 880°C are comparable to the values expected from the published diagram.[19] The mixed microstructure of lower bainite and upper bainite transformed at 426°C is shown in Fig. 22. Austenitizing at 1200°C increased the austenite grain size and a preferential effect on the hardenabilities was observed. The lower bainite hardenability remained virtually unchanged; whereas, the upper

bainitic nucleation time increased from 3 sec to 9 sec. The effect of increased hardenability with increased austenite grain size has been explained on the basis of the heterogeneous manner in which the bainite nucleates at the austenitic grain boundaries.[23] The microstructure of a specimen transformed at 500°C is shown in Figs. 20 and 30. The observed duplex microstructure was examined to determine if the difference in appearance was caused by an orientation effect. The microhardness of both regions was measured at six locations, with no difference in hardness detected. Thus it appeared that the specimen was entirely upper bainitic. Optical metallography of step-quenched specimens of 4130 transformed at 500°C did not reveal the presence of proeutectoid ferrite.

For 4140 the MPM indicated that the lower bainitic nucleation time was approximately 200 seconds greater than that shown in the published diagram.[19] The increased hardenability was attributed to the higher alloy content of the 4140 tested by the MPM method. The upper bainitic hardenability, however, was slightly lower than that reported. The microstructure of a specimen transformed at 374°C is shown in Fig. 31. Optical metallography of step-quenched specimens transformed at 500°C did not reveal the presence of proeutectoid ferrite.

The bainitic hardenabilities of D6AC, as determined with the MPM, correlated extremely well with those recently published.[21] Also, the bainite start (B_S) and bainite finish (B_F) are virtually equivalent to those previously recorded. The microstructure of a specimen held at 500°C for one hour after austenitization is shown in Fig. 32. This temperature is above the B_S so upon air quenching to room temperature, the specimen transformed to martensite. Figure 33 shows a specimen transformed for one hour

at 355°C. This transformation temperature is above the B_F; approximately 70% of the austenite had transformed to bainite before the specimen was air quenched to form martensite.

The TTT diagrams of 4130, 4140 and D6AC, which were obtained with the MPM, are in general agreement with the previously published diagrams. The TTT diagram obtained for 300-M austenitized at 880°C, however, varies significantly from the previously published diagram. The MPM diagram and the Bethlehem Steel Co. version are shown in Figs. 28 and 34, respectively.

The incubation period for the formation of bainite, as measured by the MPM, is shown to be greater by a factor of 10 over that of the previously recorded value. This difference in hardenabilities has probably resulted from the difference in austenitizing temperatures. The published information is for a 300-M, with a higher vanadium content, that was austenitized at 855°C. At 855°C all the vanadium carbides might not have been dissolved, and the lower carbon content of the matrix would cause the decomposition of austenite to start in a shorter time. Complete austenite decomposition did not occur. The austenite was only about 60% transformed. From the kinetics of transformation curves given in Figs. 16 and 17, it can be observed that most of the isothermal transformations have stabilized with time after one hour.

The microstructure of a specimen held for one hour at 500°C is shown in Fig. 23. This temperature is slightly above the B_S, so the specimen was transformed to martensite upon air quenching to room temperature. Figure 35 shows the microstructure of a specimen held at 274°C for one hour. The structure appears to be lower bainite.

Upon air quenching the specimen to room temperature the magnetic permeability of the specimen was measured. The MPM showed no further decomposition of the untransformed austenite. After holding the specimen in liquid helium (4.2°K) for 20 minutes, the magnetic permeability was again measured and showed no further decomposition. Specimens transformed for one hour at 298°C and 350°C also showed no further increase in austenite decomposition after being placed in liquid helium.

Upon austenitizing the 300-M specimens at 1200°C, the bainitic hardenability decreased, relative to that found for the lower austenitizing temperature. The upper bainite incubation period was not decreased as much as was the incubation period of lower bainite. (A decrease in hardenability with increased austenitizing temperature has also been observed by other investigators.[29,30]) Figure 29 also reveals that small percentages of austenite decomposed at the shorter incubation periods, but the 50% transformed curve occurred at virtually the same time for both austenitizing treatments. In the bainite range, the austenite decomposition did not go to completion, but began to stabilize with time, as shown in Figs. 18 and 19. After the isothermal transformation, the specimens were analyzed for decarburization. As was the case with the other steels, no change in carbon content was detected.

The microstructure of a specimen transformed at 300°C for one hour is shown in Fig. 21. The optical microstructure of a similar silicon steel appeared virtually identical to this microstructure. Transmission electron microscopy of the former steel has shown that the light etching phase is lower bainite.[31] Therefore, it is reasonable to conclude that the light etching constituent in Fig. 21 is lower bainite.

IV. CONCLUSIONS

1. The upper and lower bainite hardenabilities of AISI 4130 and AISI 4140 are in general agreement with published data on the bainite hardenabilities of these steels.
2. The martensite range temperatures for AISI 4130, AISI 4140, D6AC and AMS 6416 (300-M), that were determined with the MPM, are lower than the published values.
3. Austenitizing AISI 4130 at 1200°C increased the upper bainite nucleation time from 3 sec to 9 sec and the lower bainite nucleation time remained virtually unchanged.
4. An acceleration of the austenite decomposition occurs just above the M_s. This S-shaped transformation phenomenon is exhibited by all four of the steels and at both austenitizing temperatures.
5. Martensite forms both isothermally and athermally in AISI 4130, AISI 4140, D6AC and AMS 6416 (300-M).
6. The TTT diagram of D6AC, that was determined with the MPM, corroborates the published TTT diagram.
7. The TTT diagram of AMS 6416 (300-M), that was determined with the MPM, varies from the published data in the following manner: (a) the nucleation time for bainitic transformation (0.5%) is greater by a factor of 10. (b) the austenite decomposition did not go to completion above the M_s.
8. Austenitizing AMS 6416 (300-M) at 1200°C decreases the bainitic hardenability as compared to the bainitic hardenability obtained from austenitizing at 880°C.

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APPENDIX

```
RUN76.SC.
LGO.
EXIT.
.
      PROGRAM ERICS(INPUT.OUTPUT.TAPE98=101.PLOT.TAPE99=PLOT)
      DIMENSION DIFF(400).DIFIS(15).PCTF(15.400.2).TEMP(15).TP(15.400.2)
     1.TEMPN(15).WT(15).MFN(15).MP(9.15).KOUT(15).TDIFF(15)
      INTEGER DAT(15.400).KAT(15.400).P.PL(15).B.PAT(15.400)
C
C       I = NUMBER OF ISOTHERMAL CURVES
C       TEMPN(K) = TEMPERATURE - STRUCTURE (T-S) FACTOR
C       KAT(K.L) = FIRST DIGIT OF THE CODED INPUT.  IF EQUAL TO 9. 5.
C         OR 3 THE RECORDING INTERVAL IS 0.77. 7.7 AND 77.0 SECONDS RE-
C         SPECTIVELY.
C       KOUT(K) = NUMBER OF RECORDED INTERVALS PRIOR TO QUENCHING.
C       TP(K.M.N) = DELTA PERIOD NORMALIZED TO WEIGHT INCLUDING T-S FACTOR
C       PCTF(K.M.N) = PERCENT TRANSFORMED (HAVING ALLOWED FOR THE NON-
C         LINEARITY OF THE SIGNAL.
C
      I=15
      WTN=3.8000
      AA=0.00000069  $ BB=0.0013  $ CC= .158
      DO 104 K=1.I
  889 CONTINUE
      READ 105.TEMP(K).TEMPN(K).WT(K)
      IF(TEMP(K) .NE. 0.0) GO TO 888
      GO TO 889
  888 CONTINUE
      PRINT 200.TEMP(K)
      PRINT 105.TEMP(K).TEMPN(K).WT(K)
      M=-9  $ N=0
  102 M=M+10  $ N=N+10
      READ 101.(DAT(K.L).L=M.N)
      PRINT 101.(DAT(K.L).L=M.N)
      IF(DAT(K.N) .NE. 0)GO TO 102
      L=N
      DO 103 J=1.10
      L=L-1
      IF(DAT(K.L) .NE. 0)GO TO 704
  103 CONTINUE
  704 CONTINUE
      PRINT 500.L
  104 PL(K)=L
  101 FORMAT(10I8)
  105 FORMAT(3F10.4)
  200 FORMAT(1H1.7X.*THIS IS WHAT IS READ IN FOR TEMPERATURE*.F10.4./)
  500 FORMAT(4X.*LK =*.I8)
      ACTIM=0.0
      DO 1 K=1.I
      M=0  $ N=1  $ LK=PL(K)  $ KOUNT=0  $ K5=0  $ K3=0
      DO 1 L=1.LK
      M=M+1  $ KAT(K.L)=INT(DAT(K.L)/10     .)  $ KATKL=KAT(K.L)
      GO TO (9.9.30.9.50.9.9.80.90).KATKL
   80 ACTIM=0.0  $ KOUNT=KOUNT+1  $ KOUT(K)=KOUNT  $ A=0.0  $ B=800000
      J=1  $ GO TO 2
   90 A=0.77  $ B=900000  $ J=M  $ GO TO 2
   50 A=7.70
      IF(K5 .NE. 0) GO TO 99
```

```
      K5=1  $ A=0.77
   99 J=M  $ B=500000  $ GO TO 2
   30 A=77.
      IF(K3 .NE. 0) GO TO 55
      K3=1  $ A=7.70
   55 J=M  $ B=300000
    2 T=A+ACTIM  $ ACTIM=T  $ TP(K,M,N)=T
      DAT(K,L)=IABS(DAT(K,L)-B)
      IF(DAT(K,L)-30000)110,111,111
  110 DAT(K,L)=DAT(K,L)+100000
  111 N=N+1
      PAT(K,L)=IABS(DAT(K,L)-DAT(K,1))
      IF(PAT(K,L) .LT. 0) GO TO 9
      TP(K,M,N)=PAT(K,L)*(WTN/WT(K))*TEMPN(K)
      N=1
    1 M=J
      DO 339 L=1,I
  339 PL(L)=PL(L)-KOUT(L)
      DO 600 K=1,I
      NN=PL(K)-1  $ J=0
      DO 600 M=1,NN
      DIFF(M)=TP(K,M+1,2)-TP(K,1,2)
      IF(DIFF(M) .GE. DIFF(M-J)) GO TO 601
      TDIFF(K)=DIFF(M-J)
      GO TO 607
  601 TDIFF(K)=DIFF(M)
  607 CONTINUE
  600 J=1
      DO 368 K=1,I
      PRINT 578,TDIFF(K),K
  368 CONTINUE
  578 FORMAT(6X,*TDIFF(K) =*,F8.2,3X,*K = *,I3)
      IK=I-1
      MAX=1
      DO 604 J=1,IK
      IF((TDIFF(J+1)-TDIFF(J)) .GT. 0.0) GO TO 961
      TDIFF(J+1)=TDIFF(J)
      GO TO 604
  961 MAX=J+1
  604 CONTINUE
      PRINT 587,MAX,TDIFF(I)
  587 FORMAT(3X,*MAX =*,I3,3X,*TDIFF(I)=*,F8.2)
      DO 705 K=1,I
      MFN(K)=PL(K)  $ NK=PL(K)
      DO 605 M=2,NK
      TT=TP(K,M,2)-TP(K,1,2)
      PCTF(K,M,2)=((AA*(TT**2)+BB*TT+CC)*100.)/(AA*(TDIFF(I))**2+BB*TDIF
     1F(I)+CC)
      IF(PCTF(K,M,2) .GE. 0.0) GO TO 901
      PCTF(K,M,2)=0.006
  901 CONTINUE
  605 PCTF(K,M,1)=TP(K,M,1)
      PRINT 805,PCTF(K,NK,2)
  705 CONTINUE
  805 FORMAT(50X,*PCTF(K,NK,2) =*,F8.2)
      DO 330 K=1,I
      DO 330 J=1,8
  330 MP(J,K)=2
```

```
      DO 210 K=1,I
      LK=MFN(K)
      DO 300 MP5=2,LK
      IF(PCTF(K,MP5,2)-0.5)300,300,301
  300 MP(1,K)=MP5
  301 CONTINUE
      DO 201 M=MP5,LK
      IF(PCTF(K,M,2)-1.0)201,201,202
  201 MP(2,K)=M
  202 CONTINUE
      DO 302 M5=M,LK
      IF(PCTF(K,M5,2)-5.0)302,302,303
  302 MP(3,K)=M5
  303 CONTINUE
      DO 304 M10=M5,LK
      IF(PCTF(K,M10,2)-10.0)304,304,3 5
  304 MP(4,K)=M10
  305 CONTINUE
      DO 306 M25=M10,LK
      IF(PCTF(K,M25,2)-25.0)306,306,3 7
  306 MP(5,K)=M25
  307 CONTINUE
      DO 203 J=M25,LK
      IF(PCTF(K,J,2)-50.0)203,203,204
  203 MP(6,K)=J
  204 CONTINUE
      DO 308 M75=J,LK
      IF(PCTF(K,M75,2)-75.0)308,308,3 9
  308 MP(7,K)=M75
  309 CONTINUE
      DO 205 L=M75,LK
      IF(PCTF(K,L,2)-90.)205,205,206
  205 MP(8,K)=L
      PRINT 207,TEMP(K)
  207 FORMAT(5X,*NINETY PERCENT HAS NOT TRANSFORMED FOR TEMPERATURE =*,
     1F10.4)
      GO TO 210
  206 CONTINUE
      PRINT 208,TEMP(K)
  208 FORMAT(3X,*MORE THAN NINETY PERCENT HAS TRANSFORMED FOR TEMPERATUR
     1E = *,F10.4)
      PRINT 710,PCTF(K,L,2)
  710 FORMAT(12X,*PCTF(K,L,2) =*,F7.2)
  210 CONTINUE
      KOUNT=1  $ YMI=-2.0  $ YMA=0.0
  333 CONTINUE
      CALL GRAPHM(I,MFN,KOUNT,PCTF,YMI,YMA,MP)
      KOUNT=KOUNT+1  $ YMI=-1.0  $ YMA=1.0
      IF(KOUNT .EQ. 2) GO TO 333
      CALL GRAFTT(I,TEMP,PCTF,MP)
      GO TO 999
    9 CONTINUE
      PRINT 909
  909 FORMAT(9X,/,*THERE IS AN ERROR IN THE DATA*)
      GO TO 999
 2001 CONTINUE
      PRINT 2002
 2002 FORMAT(3X,*THERE IS NOT ENOUGH TRANSFORMED*)
```

```
999 CONTINUE
    CALL CCEND
    STOP
    END
    SUBROUTINE GRAPHT(I,PL,KOUNT,PCTF,YMI,YMA)
    COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
    COMMON/CCFACT/FACTOR
    DIMENSION XT(400),YT(400),PCTF(15,400,2)
    INTEGER PL(15)
C
C       THIS SUBROUTINE PLOTS PERCENT TRANSFORMED VERSUS TIME.
C
    XMIN=0.  $ XMAX=3600.  $ FACTOR=1.  $ CCXMIN=100.  $ CCXMAX=1500.
    CCYMIN=100.  $ CCYMAX=1000.  $ YMIN=0.  $ YMAX=100.0
    CALL CCGRID(4,5,6HLABELS,4,5)
    DO 3 K=1,I
    PRINT 441,PL(K)
441 FORMAT(16X,*GRAPHT--MFN(K) =*,I6)
    N=PL(K)-1  $ NS=1  $ LK=PL(K)
    DO 112 J=2,LK
    JM=J-1  $ XT(JM)=PCTF(K,J,1)
112 YT(JM)=PCTF(K,J,2)
    CALL CCPLOT(XT,YT,N,4HJOIN,NS,1)
  3 CONTINUE
    CALL CCLTR(500.,10.,0.2,9HTIME(SEC),9)
    CALL CCLTR(10.,340.,1.2,19HPERCENT TRANSFORMED,19)
    CALL CCNEXT
    RETURN
    END
```

```
    SUBROUTINE GRAPHM(I,PL,KOUNT,PCTF,YMI,YMA,MP)
    COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
    COMMON/CCFACT/FACTOR
    DIMENSION X(400),Y(400),PCTF(15,4  ,2),MP(9,15)
    INTEGER PL(15)
C
C       THIS SUBROUTINE PLOTS THE DATA WHEN FITTED TO THE JOHNSON-MEHL
C          AND AUSTEN-RICKETT EQUATIONS.
C
    XMIN=ALOG10(1.0)  $ XMAX=ALOG10(1     .0)  $ CCXMAX=3000.0
    YMIN=YMI  $ YMAX=YMA  $ NLYP=2  $ NLYS=2  $ NCY=0  $ NCX=4
    TICLL=0.100  $ TICLL1=0.167
    DO 807 J=1,4
    KAXIS=J
    CALL CCLOGTC(KAXIS,NCY,NCX,TICLL,TICLL1,NLYP,NLYS)
807 CONTINUE
    CALL CLBLLGX(NCX)
    LINY=NLYP  $ LINX=0
    CALL CCLBL(LINX,LINY)
    MM=0
    DO 3 K=8,13
    N=PL(K)-2  $ MM=MM+1
    GO TO (1,2,4,5,6,8),MM
  1 NS=8
    GO TO 7
  2 NS=6
    GO TO 7
  4 NS=1
    GO TO 7
```

```
    5 NS=7
      GO TO 7
    6 NS=9
      GO TO 7
    8 NS=5
    7 CONTINUE
      LK=PL(K)
      DO 112 J=3,LK
      JM=J-2
      IF(PCTF(K,J,2) .GT. 10.) GO TO 21
      LO=MP(4,K)  $ PCTF(K,J,1)=PCTF(K,LO,1)  $ PCTF(K,J,2)=PCTF(K,LO,2)
      GO TO 211
  210 CONTINUE
      IF(PCTF(K,J,2) .LT. 90.) GO TO 211
      LN=MP(8,K)  $ PCTF(K,J,1)=PCTF(K,LN,1)  $ PCTF(K,J,2)=PCTF(K,LN,2)
  211 X(JM)=ALOG10(PCTF(K,J,1))
      IF( KOUNT - 1)543,543,542
  543 Y(JM)=ALOG10(ALOG10(1.0/(1.0-(PCTF(K,J,2)/1  .))))
      GO TO 538
  542 Y(JM)=ALOG10((PCTF(K,J,2)/100.0)/(1.0-(PCTF(K,J,2)/100.0)))
  538 CONTINUE
      IF(Y(JM) .GT. YMI) GO TO 10
      PRINT 11,X(JM),Y(JM),K,J
   11 FORMAT(4X,*X(JM) =*,F8.5,2X,*Y(JM) =*,F8.5,4X,*K =*,I3,2X,*J=*,I3)
      Y(JM)=YMI
   10 CONTINUE
      IF(X(JM) .GE. ALOG10(1.0)) GO TO 552
      X(JM)=ALOG10(1.0)
  552 CONTINUE
  112 CONTINUE
      CALL CCPLOT(X,Y,N,4HJOIN,NS,1)
    3 CONTINUE
      CALL CCLTR(460.,10.,0.2,15HLOG  TIME (SEC),15)
      IF(KOUNT - 1)541,541,540
  541 CONTINUE
      CALL CCLTR(10.,330.,1.2,28HLOG  LOG  (1/1-Y)      J-M EQ.28)
      GO TO 539
  540 CONTINUE
      CALL CCLTR(10.,330.,1.2,24HLOG  (Y/1-Y)      A-R EQ.24)
  539 CONTINUE
      CALL CCNEXT
      RETURN
      END
      SUBROUTINE GRAPHR(I,PL,KOUNT,PCTF,YMI,YMA)
      COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
      COMMON/CCFACT/FACTOR
      DIMENSION XR(400),YR(400),PCTF(15,400,2)
      INTEGER PL(15)
C
C        THIS SUBROUTINE PLOTS LOG PERCENT TRANSFORMED VERSUS LOG TIME.
C
      XMIN=0.0  $ XMAX=ALOG10(10000.0)  $ CCXMAX=1500.0  $ YMIN=0.0
      YMAX=ALOG10(100.)
      DO 808 J=1,4
      KAXIS=J  $ NCY=2  $ NCX=4  $ TICLL=0.100  $ TICLL1=0.167
      CALL CCLOGTC(KAXIS,NCY,NCX,TICLL,TICLL1,NLYP,NLYS)
  808 CONTINUE
      CALL CLBLLGY(NCY)
```

```
      CALL CLBLLGX(NCX)
      DO 3 K=1,I
      N=PL(K)-2  $ NS=1  $ LK=PL(K)
      DO 112 J=3,LK
      JM=J-2  $ XR(JM)=ALOG10(PCTF(K,J,1))  $ YR(JM)=ALOG10(PCTF(K,J,2))
      IF(XR(JM) .GE. ALOG10(1.0)) GO TO 552
      XR(JM)=ALOG10(1.0)
  552 CONTINUE
      IF(YR(JM) .GE. 0.0)GO TO 553
      YR(JM)=0.0
  553 CONTINUE
  112 CONTINUE
      CALL CCPLOT(XR,YR,N,4HJOIN,NS,1)
    3 CONTINUE
      CALL CCLTR(460.,10.,0.2,15HLOG  TIME (SEC),15)
      CALL CCLTR(10.,330.,1.2,23HLOG PERCENT TRANSFORMED,23)
      CALL CCNEXT
      RETURN
      END
      SUBROUTINE GRAPHK(I,TEMP,NU)
      COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
      COMMON/CCFACT/FACTOR
      DIMENSION X(15),Y(15),TEMP(15),RK(15)

        THIS SUBROUTINE PLOTS THE INVERSE TEMPERATURE VERSUS LOG INVERSE
          OF INTERCEPT OF THE ISOTHERMAL CURVES.

      XMIN=12.0  $ XMAX=17.0  $ YMIN= 3.0  $ YMAX=0.0  $ CCXMAX=1200.0
      CALL CCGRID(5,2,5HLABELS,3,4)
      RK(10)=11.0  $ RK(11)=8.1  $ RK(12)=7.4  $ RK(13)=6.4
      RK(14)=7.3  $ RK(15)=4.7
      DO 3 K=NU,I
      J=1  $ N=1  $ NS=6
      X(J)=10000.0/(TEMP(K)+273.0)
      Y(J)=ALOG10(1./RK(K))
      CALL CCPLOT(X,Y,N,6HNOJOIN,NS,1)
    3 CONTINUE
      CALL CCLTR(460.,10.,0.2,18H1000 /T   (KELVIN),18)
      CALL CCLTR(10.,380.,1.2,8HLOG(1/K),8)
      CALL CCNEXT
      RETURN
      END
      SUBROUTINE GRAFTT(I,TEMP,PCTF,MP)
      COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
      COMMON/CCFACT/FACTOR
      DIMENSION XTT(15),YTT(15),PCTF(15,400,2),TEMP(15),MP(9,15),XS(15),
     1YS(15)
C
C       THIS SUBROUTINE PLOTS THE TIME   TEMPERATURE - TRANSFORMATION DIAGRAM.
C
      XMIN=ALOG10(1.0)  $ XMAX=ALOG10(1     .0)  $ CCXMAX=1600.0
      YMIN=0.0  $ YMAX=600.0  $ NLYP=6  $ NLYS=2  $ NCY=0  $ NCX=4
      TICLL=0.100  $ TICLL1=0.167
      DO 807 J=1,4
      KAXIS=J
      CALL CCLOGTC(KAXIS,NCY,NCX,TICLL,TICLL1,NLYP,NLYS)
  807 CONTINUE
      CALL CLBLLGX(NCX)
```

```
      LINY=NLYP  $ LINX=0
      CALL CCLBL(LINX,LINY)
      DO 3 L=1,8
      N=I
      GO TO (1,2,4,5,6,7,8,9),L
    1 NS=8
      GO TO 10
    2 NS=6
      GO TO 10
    4 NS=8
      GO TO 10
    5 NS=8
      GO TO 10
    6 NS=8
      GO TO 10
    7 NS=7
      GO TO 10
    8 NS=8
      GO TO 10
    9 NS=7
   10 CONTINUE
      DO 112 J=1,I
      M=MP(L,J)
      IF(PCTF(J,M,1) .GT. 2.) GO TO 4
      PRINT 401,PCTF(J,M,1),J
  401 FORMAT(6X,*PCTF(J,M,1)=*,F10.3,4X,*J =*,I6)
      PCTF(J,M,1)=1.0
  400 CONTINUE
      XTT(J)=ALOG10(PCTF(J,M,1))
      IF(XTT(J) .GE. ALOG10(1.4)) GO TO 554
      XTT(J)=ALOG10(1.0)
  554 CONTINUE
      YTT(J)=TEMP(J)  $ XS(J)=PCTF(J,M,1)  $ YS(J)=TEMP(J)
      PRINT 1021,XS(J),YS(J)
 1021 FORMAT(5X,*XTT(J)=*,F10.4,3X,*YTT(J) =*,F10.4)
  112 CONTINUE
      CALL CCPLOT(XTT,YTT,N,6HNOJOIN,NS,1)
    3 CONTINUE
      CALL CCLTR(470.,10.,0,2,15HLOG  TIME (SEC),15)
      CALL CCLTR(10.,340.,1,2,15HTEMPERATURE (C),15)
      CALL CCNEXT
      RETURN
      END
      SUBROUTINE CCLOGTC(KAXIS,NCY,NCX,TICLL,TICLL1,NLYP,NLYS)
C     THIS SUBROUTINE PLOTS LOG SPACED TIC MARKS USING THE CAL COMP ROUTINES
C     KAXIS OF 1=LOWER AXIS, 2=RIGHT HAND AXIS, 3=UPPER AXIS, 4=LEFT HAND AXIS
C     NC=NUMBER OF CYCLES
C     TICLL=LENGTH OF SECONDARY TIC MARKS IN INCHES
C     TICLL1=LENGTH OF PRIMARY TIC MARKS IN INCHES
      COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
      COMMON/CCFACT/FACTOR
      DIMENSION XTIC(30),YTIC(30)
      X1SAVE=XMIN $ X2SAVE=XMAX $ Y1SAVE=YMIN $ Y2SAVE=YMAX
      GO TO (100,110,120,130),KAXIS
  100 XMIN=0.  $ XMAX=FLOAT( NCX)  $ YMIN=0.  $ YMAX=1.0
      B=100./(FACTOR*(CCYMAX-CCYMIN))
      GO TO 208
  110 XMIN=1.  $ XMAX=0.  $ YMIN=0.
```

```
      IF(NCY .GT. 0) GO TO 501
      YMAX=(FLOAT(NLYP))*100.
      GO TO 502
  501 YMAX=FLOAT(NCY)
  502 CONTINUE
      B=100./(FACTOR*(CCXMAX-CCXMIN))
      GO TO 300
  120 XMIN=0.  $ XMAX=FLOAT(NCX) $ YMIN=1.  $ YMAX=0.
      B=100./(FACTOR*(CCYMAX-CCYMIN))
      GO TO 208
  130 XMIN=0.  $ XMAX=1.  $ YMIN=0.
      IF(NCY .GT. 0) GO TO 504
      YMAX=(FLOAT(NLYP))*100.
      GO TO 505
  504 YMAX=FLOAT(NCY)
  505 CONTINUE
      B=100./(FACTOR*(CCXMAX-CCXMIN))
  300 NC=NCY
      GO TO 200
  208 NC=NCX
  200 TICL=TICLL*B
      TICL1=TICLL1*B
      IF(NC .EQ. 0) GO TO 400
      DO 205 K=1,NC
      L=1
      DO 204 J=1,9
      AJ=J
      XTICC=ALOG10(AJ)+K-1.
      DO 203 I=1,3
      XTIC(L)=XTICC
      GO TO (201,202,201),I
  201 YTIC(L)=0.
      GO TO 203
  202 YTIC(L)=TICL
      IF ((J.EQ.1).AND.(K.NE.1)) YTIC(L)=TICL1
  203 L=L+1
  204 CONTINUE
      XTIC(L)=K
      YTIC(L)=0.
      GO TO (206,207,206,207),KAXIS
  206 CALL CCPLOT(XTIC,YTIC,L,4HJOIN)
      GO TO 205
  207 CALL CCPLOT (YTIC,XTIC,L,4HJOIN)
  205 CONTINUE
      GO TO 500
  400 CONTINUE
      THUD=100.0
      DO 405 K=1,NLYP
      L=1
      DO 404 J=1,NLYS
      AJ=J
      XTICC=((AJ+K-1.)*100.)-THUD
      DO 403 I=1,3
      XTIC(L)=XTICC
      GO TO (401,402,401),I
  401 YTIC(L)=0.
      GO TO 403
  402 YTIC(L)=TICL
```

```
      IF((J.EQ.1).AND.(K.NE.1)) YTIC(L)=TICL1
  403 L=L+1
      THUD=0.0
  404 CONTINUE
      XTIC(L)=K*100.
      YTIC(L)=0.
      CALL CCPLOT(YTIC,XTIC,L,4HJOIN)
  405 CONTINUE
  500 CONTINUE
      XMIN=X1SAVE $ XMAX=X2SAVE $ YMIN=Y1SAVE $ YMAX=Y2SAVE
      RETURN
      END
      SUBROUTINE CLBLLGY (NC)
       COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
       COMMON/CCFACT/FACTOR
C
C  ROUTINE LABELS Y AXIS IN LOG SCALE.
C
      NX = NC + 1
      DO 1 I = 1, NX
      WRITE (98, 300)
      CCY = CCYMIN + (I-1)*(CCYMAX-CCYMIN) / NC -  .1
      CALL CCLTR(CCXMIN-65.,CCY,0,2)
      I2 = ( YMIN+SIGN(.5,YMIN) ) + I   1
      IF ( +ABS(I2) .GT. 9 )  GO TO 2
      IF ( I2 .EQ. 0 )  I2 = +0
      WRITE (98,302) I2
      GO TO 3
    2 WRITE (98, 301) I2
    3 CALL CCLTR(CCXMIN-40.,CCY+10.,0,1)
    1 CONTINUE
C
      RETURN
  300 FORMAT ( 2H10 )
  301 FORMAT ( I3 )
  302 FORMAT ( I2 )
      END
      SUBROUTINE CLBLLGX(NCX)
      COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
      COMMON/CCFACT/FACTOR
C
C    ROUTINE LABELS X AXIS IN LOG SCALE.
C
      NX=NCX+1
      DO 1 I=1,NX
      WRITE (98, 300)
      CCX=CCXMIN+(I-1)*(CCXMAX-CCXMIN)/NCX-0.1
      CALL CCLTR(CCX,CCYMIN-40.,0,2)
      I2=(XMIN+SIGN(.5,XMIN))+I-1
      IF(IABS(I2) .GT. 9) GO TO 2
      IF(I2 .EQ. 0) I2=+0
      WRITE(98,302)I2
      GO TO 3
    2 WRITE(98,301)I2
    3 CALL CCLTR(CCX+25.,CCYMIN-25.,0,1)
    1 CONTINUE
C
      RETURN
```

```
  300 FORMAT ( 2H10 )
  301 FORMAT ( I3 )
  302 FORMAT ( I2 )
      END
       SUBROUTINE CCLBL(NX1,NY1)
       COMMON/CCPOOL/XMIN,XMAX,YMIN,YMAX,CCXMIN,CCXMAX,CCYMIN,CCYMAX
       COMMON/CCFACT/FACTOR
       ISZERO=0
       XD=XMAX-XMIN            $YD=YMAX YMIN
       CCXD=CCXMAX-CCXMIN      $CCYD=CCYMAX-CCYMIN
C
      KSIZE=2
      KORIENT = 0
      IF ( NX1 .EQ. 0 )  GO TO 5
C
C      LABEL FROM RIGHT TO LEFT ALONG THE X-AXIS.
C
      XI=XD/FLOAT(NX1)
       DO 2 NX=ISZERO,NX1
       CCX=CCXMAX-CCXD*FLOAT(NX)/FLOAT(NX1)
       X=(CCX-CCXMIN)*XD/CCXD+XMIN
C
C      SET X TO A TRUE ZERO IF X=0. TO WITHIN MACHINE ACCURACY.
C
       IF(ABS (X/XI).LT.1.0E-6)X=0.
      NN = IFIX (X + .1)
      WRITE (98,27) NN
    2 CALL CCLTR (CCX-65.*FLOAT(KSIZE)/FACTOR,
     X              CCYMIN-9.*FLOAT(KSIZE)/FACTOR,
     X              KORIENT, KSIZE )
C
    5 IF ( NY1 .EQ. 0 )  RETURN
C
C      LABEL UPWARD ALONG THE Y-AXIS.
C
       YI=YD/FLOAT(NY1)
       DO 3 NY=ISZERO,NY1
       CCY=CCYMIN+CCYD*FLOAT(NY)/FLOAT(NY1)
       Y=(CCY-CCYMIN)*YD/CCYD+YMIN
C
C      SET Y TO A TRUE ZERO IF Y=0. TO WITHIN MACHINE ACCURACY.
C
       IF(ABS (Y/YI).LT.1.0E-6)Y=0.
       IF (Y) 100, 101, 102
  100 NM = IFIX (Y-.1)   $   GO TO 104
  101 NM = 0   $   GO TO 104
  102 NM = IFIX (Y+.1)
  104 WRITE (98,28) NM
    3 CALL CCLTR(CCXMIN-70.*FLOAT(KSIZE)/FACTOR,CCY,KORIENT,KSIZE)
C
       RETURN
C
   27 FORMAT (I10)
   28 FORMAT (I10)
       END
```

REFERENCES

1. J. S. Pascover and S. J. Matas, Structure and Properties of Ultrahigh-Strength Steels, ASTM STP 370 (American Society for Testing and Materials, Philadelphia, 1965), p. 33.
2. Y. H. Liu, Trans. Amer. Soc. Metals 62, 544 (1969).
3. W. E. Wood. E. R. Parker and V. F. Zackay, LBL-1474, Lawrence Berkeley Laboratory, Berkeley, California, May 1973.
4. J. Burke, The Kinetics of Phase Transformations in Metals (Pergamon Press, 1965), p. 37.
5. F. B. Rote, W. C. Truckenmiller and W. P. Wood, Trans. ASM 30, 1359 (1942).
6. A. L. Christenson, E. C. Nelson and C. E. Jackson, Trans. AIME 162, 606 (1945).
7. R. L. Rickett and F. C. Kristufek, Trans. ASM 41, 1113 (1949).
8. C. Nagler and W. P. Wood, Trans. ASM 491 (1942).
9. H. A. Smith, Trans. AIME 116, 342 (1935).
10. W. Hume-Rothery, The Structures of Alloys of Iron (Pergamon Press, 1966), p. 176.
11. W. A. Backoften and M. L. Ebner, Metallurgical Aspects of Fracture of High Strength Steels, Final Tech. Report (Watertown Arsenal Laboratory, Massachusetts, 1963).
12. B. N. P. Babu, Ph. D. Thesis, University of California, Berkeley, California (to be published).
13. R. E. Reed-Hill, Physical Metallurgy Principles (Van Nostrad Reinhold Company, New York, 1964), p. 459.

14. A. R. Entwisle, Met. Trans. 2, 2395 (1971).

15. A. B. Greninger and A. R. Troiano, Trans. ASM 28, 537 (1940).

16. W. Steven and A. G. Haynes, J. Iron Steel Inst. 183, 349 (1956).

17. R. M. Bozorth, Ferromagnetism (D. Van Nostrad, New York, 1951), p. 59.

18. Ibid, p. 714.

19. Isothermal Transformation Diagrams (United States Steel, 1963).

20. Isothermal Transformation Diagrams of Nickel Alloy Steels (International Nickel Company, Inc., 1965).

21. T. J. Koppenaal, Met. Trans. 1, 3371 (1970).

22. R. E. Reed-Hill, Physical Metallurgy Principles (Van Nostrand Reinhold Company, New York, 1964), p. 500.

23. B. L. Averbach and M. Cohen, Trans. ASM 41, 1024 (1949).

24. Charles Barrett and T. B. Massalski, Structure of Metals (McGraw-Hill Book Company, Inc., New York, 1966), p. 399.

25. R. T. Howard and M. Cohen, Trans. AIME 176, 384 (1948).

26. O. Schaaber, J. Metals 7, 559 (1955).

27. S. V. Radcliffe and E. C. Rollason, J. Iron Steel Inst. 191, 56 (1959).

28. M. A. Grossman, Elements of Hardenability (ASM, Cleveland, 1952).

29. S. A. Cottrell and T. Ko, J. Iron Steel Inst. 173, 224 (1953).

30. L. W. Graham and H. J. Axon, J. Iron Steel Inst. 191, 361 (1959).

31. G. Lai, (to be published).

Table I. Chemical composition of alloys (given in wt%).

Alloy	C	Mn	Cr	Ni	Mo	S	Si	Cu	P	V
D6AC	0.46	0.68	0.98	0.58	0.83	0.003	0.25	----	0.009	0.11
AMS 6416 (300-M)	0.41	0.79	0.75	1.85	0.43	0.002	1.59	0.04	0.008	0.08
AISI 4140	0.40	0.94	0.90	0.09	0.22	0.012	0.28	0.17	0.008	*
AISI 4130	0.34	0.51	0.95	0.16	0.19	0.014	0.27	0.11	0.008	*

*Less than 0.0057.

Table II. Cooling times of AISI 4140 specimens.

Specimen Thickness	Quench Medium Temperature			
	25°C	225°C	325°C	425°C
0.02	1.4 sec	1.0 sec	0.8 sec	0.7 sec
0.03	1.8 sec	1.5 sec	1.2 sec	1.0 sec

Table III. Comparison of martensite range temperatures (°C).

Material	M_s		M_{50}		M_{90}	
	MPM Values	Published Values	MPM Values	Published Values	MPM Values	Published Values
AISI 4140						
Aust. at 880°C	295	340[19]	200	300[19]	90	270[19]
D6AC						
Aust. at 880°C	290	290[21]	170	-----	50	-----
AISI 4130						
Aust. at 880°C	340	360[19]	250	320[19]	150	300[19]
Aust. at 1200°C	350	-----	250	-----	150	-----
AMS 6416 (300-M)						
Aust. at 880°C	270	300[20]	170	-----	60	-----
Aust. at 1200°C	290	-----	190	-----	60	-----

FIGURE CAPTIONS

Fig. 1. Schematic of the MPM apparatus.

Fig. 2. Block diagram of the MPM electronic system.

Fig. 3. Temperature-structure calibration curve of 4140.

Fig. 4. Temperature-structure calibration curve of 4130.

Fig. 5. Temperature-structure calibration curve of D6AC.

Fig. 6. Temperature-structure calibration curve of 300-M.

Fig. 7. Volume fraction transformed calibration curve.

Fig. 8. Percent transformed vs time for 4140 austenitized at 880°C.

Fig. 9. Log percent transformed vs log time for 4140 austenitized at 880°C.

Fig. 10. Percent transformed vs time for 4130 austenitized at 880°C.

Fig. 11. Log percent transformed vs log time for 4130 austenitized at 880°C.

Fig. 12. Percent transformed vs time for 4130 austenitized at 1200°C.

Fig. 13. Log percent transformed vs log time for 4130 austenitized at 1200°C.

Fig. 14. Percent transformed vs time for D6AC austenitized at 880°C.

Fig. 15. Log percent transformed vs time for D6AC austenitized at 880°C.

Fig. 16. Percent transformed vs time for 300-M austenitized at 880°C.

Fig. 17. Log percent transformed vs log time for 300-M austenitized at 880°C.

Fig. 18. Percent transformed vs time for 300-M austenitized at 1200°C.

Fig. 19. Log percent transformed vs log time for 300-M austenitized at 1200°C.

Fig. 20. Microstructure of 4130 after austenitizing for 15 minutes at 1200°C and isothermally transformed for 2 hours at 500°C (1200°C, 500°C).

Fig. 21. Microstructure of 300-M after a (1200°C, 300°C) heat treatment.

Fig. 22. Microstructure of 4130 after a (880°C, 426°C) heat treatment.

Fig. 23. Microstructure of 300-M after a (880°C, 500°C) heat treatment.

Fig. 24. Time-temperature-transformation diagram of 4140 austenitized at 880°C.

Fig. 25. Time-temperature-transformation diagram of 4130 austenitized at 880°C.

Fig. 26. Time-temperature-transformation diagram of 4130 austenitized at 1200°C.

Fig. 27. Time-temperature-transformation diagram of D6AC austenitized at 880°C.

Fig. 28. Time-temperature-transformation diagram of 300-M austenitized at 880°C.

Fig. 29. Time-temperature-transformation diagram of 300-M austenitized at 1200°C.

Fig. 30. Enlargement of micrograph in Fig. 20.

Fig. 31. Microstructure of 4140 after a (880°C, 374°C) heat treatment.

Fig. 32. Microstructure of D6AC after a (880°C, 500°C) heat treatment.

Fig. 33. Microstructure of D6AC after a (880°C, 355°C) heat treatment.

Fig. 34. Time-temperature-transformation diagram of 300-M austenitized at 855°C (Bethlehem Steel Co. version, see Ref. 20).

Fig. 35. Microstructure of 300-M after a (880°C, 274°C) heat treatment.

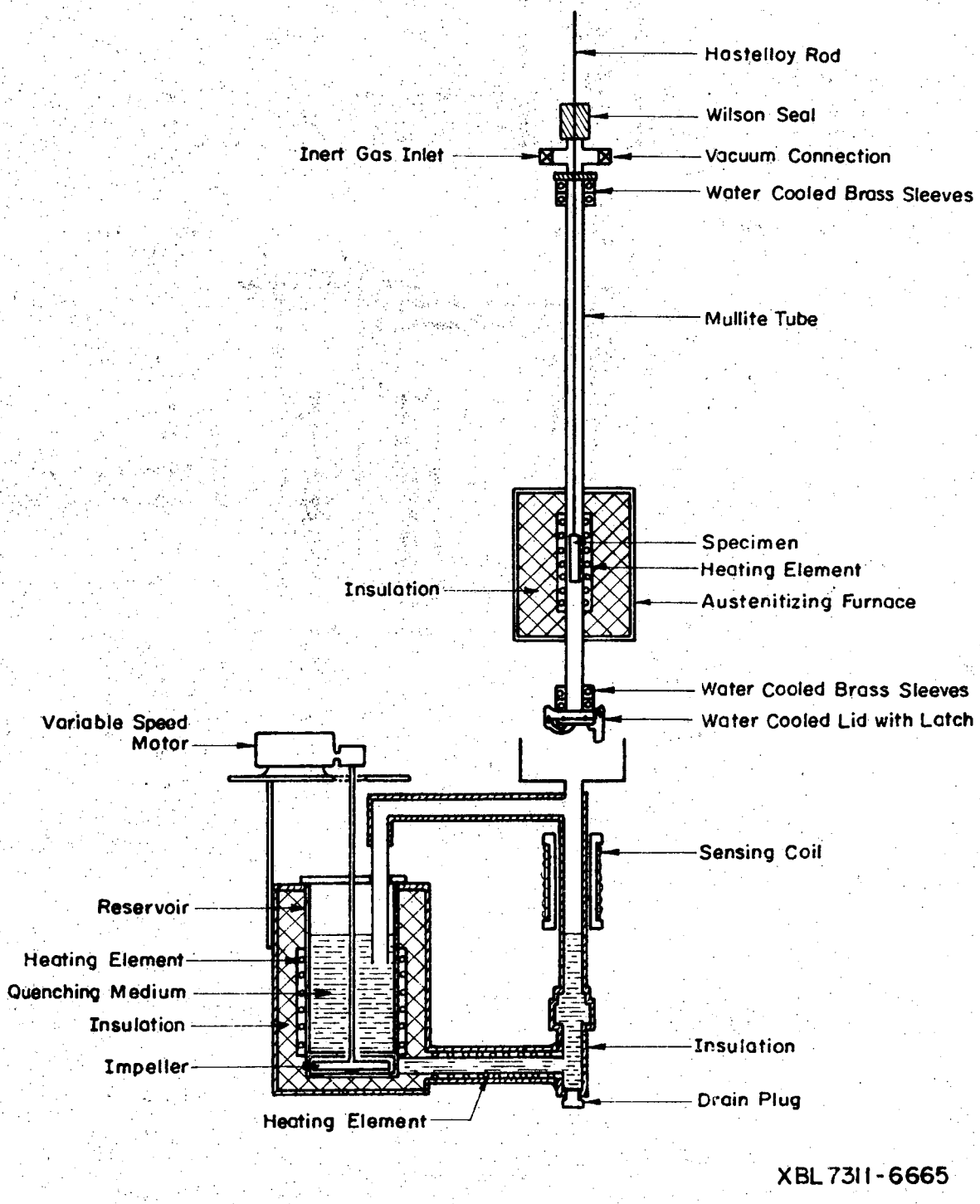

Hastelloy Rod
Wilson Seal
Inert Gas Inlet
Vacuum Connection
Water Cooled Brass Sleeves
Mullite Tube
Specimen
Heating Element
Insulation
Austenitizing Furnace
Water Cooled Brass Sleeves
Water Cooled Lid with Latch
Variable Speed Motor
Sensing Coil
Reservoir
Heating Element
Quenching Medium
Insulation
Insulation
Impeller
Drain Plug
Heating Element
XBL 7311-6665

Fig. 1

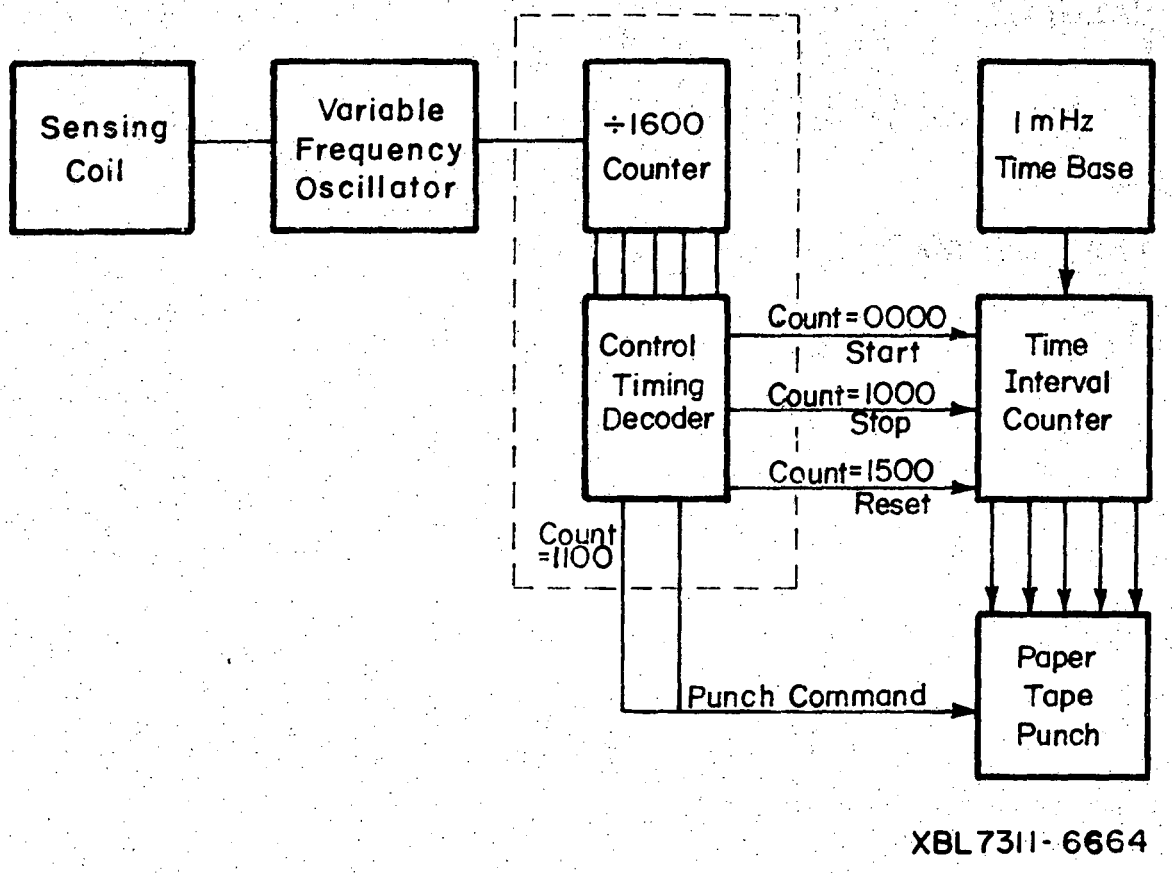

Sensing Coil
Variable Frequency Oscillator
÷1600 Counter
1 mHz Time Base
Control Timing Decoder
Count=0000 Start
Count=1000 Stop
Count=1500 Reset
Time Interval Counter
Count =1100
Punch Command
Paper Tape Punch
XBL7311-6664

Fig. 2

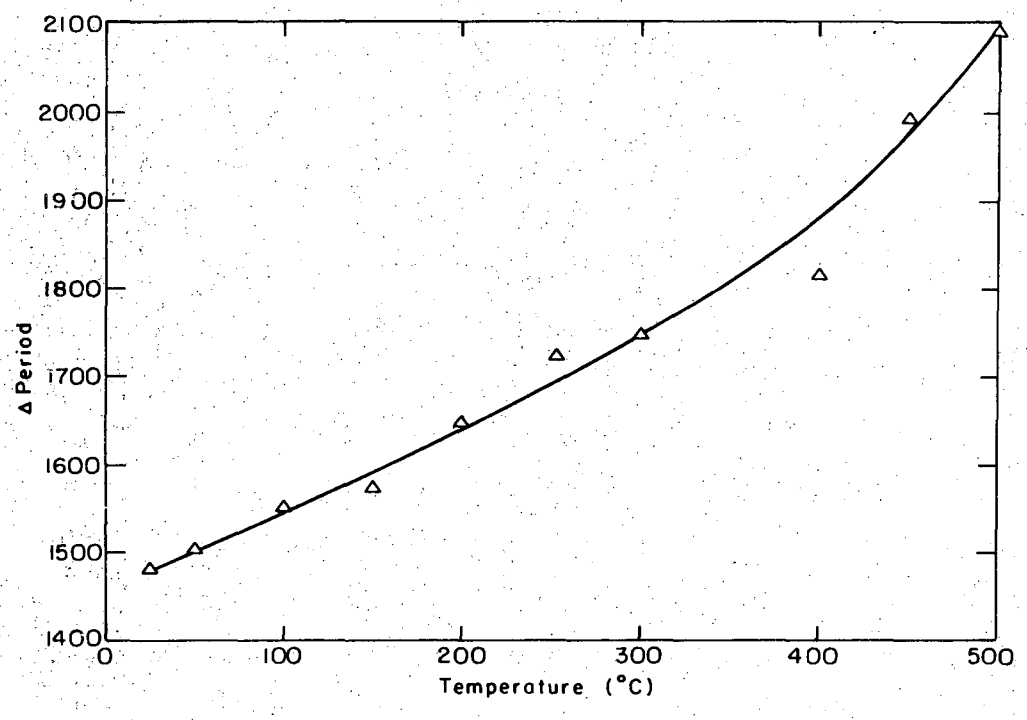

2100
2000
1900
1800
1700
1600
1500
1400
Δ Period
0
100
200
300
400
500
Temperature (°C)

Fig. 3

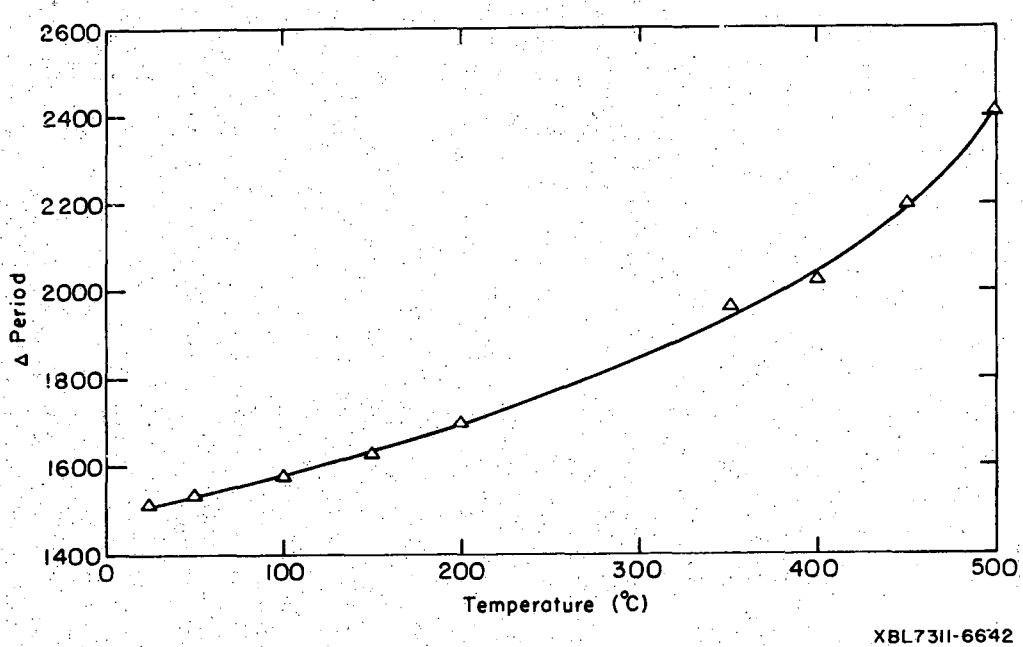

2600
2400
2200
2000
1800
1600
1400
Δ Period
0
100
200
300
400
500
Temperature (°C)
XBL7311-6642

Fig. 4

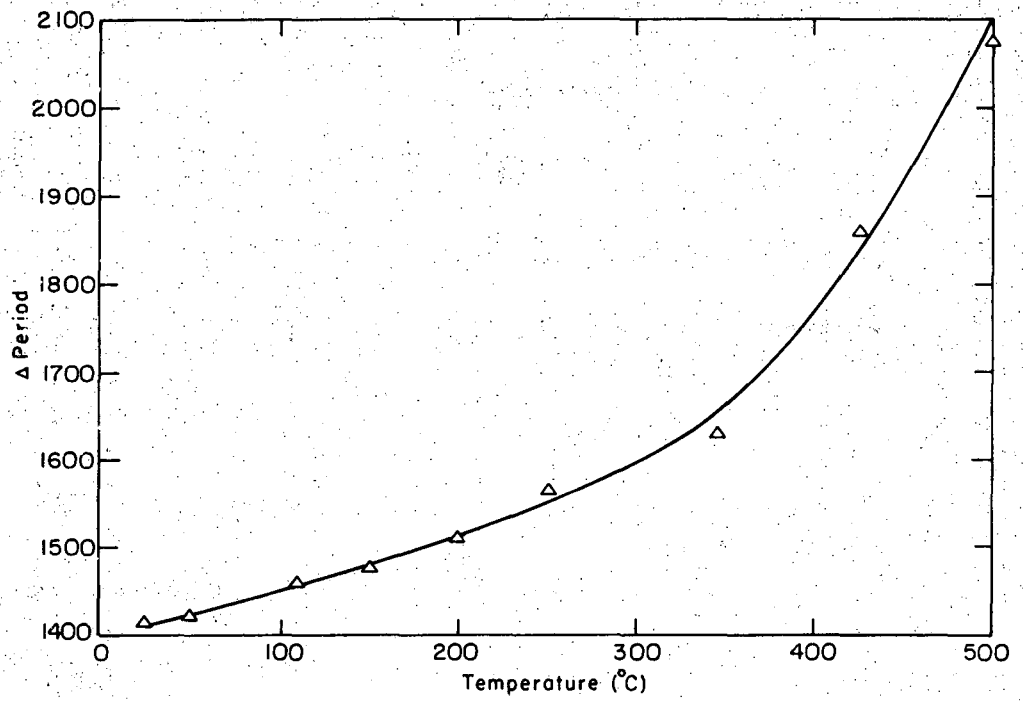

2100
2000
1900
1800
1700
1600
1500
1400
Δ Period
0
100
200
300
400
500
Temperature (°C)

Fig. 5

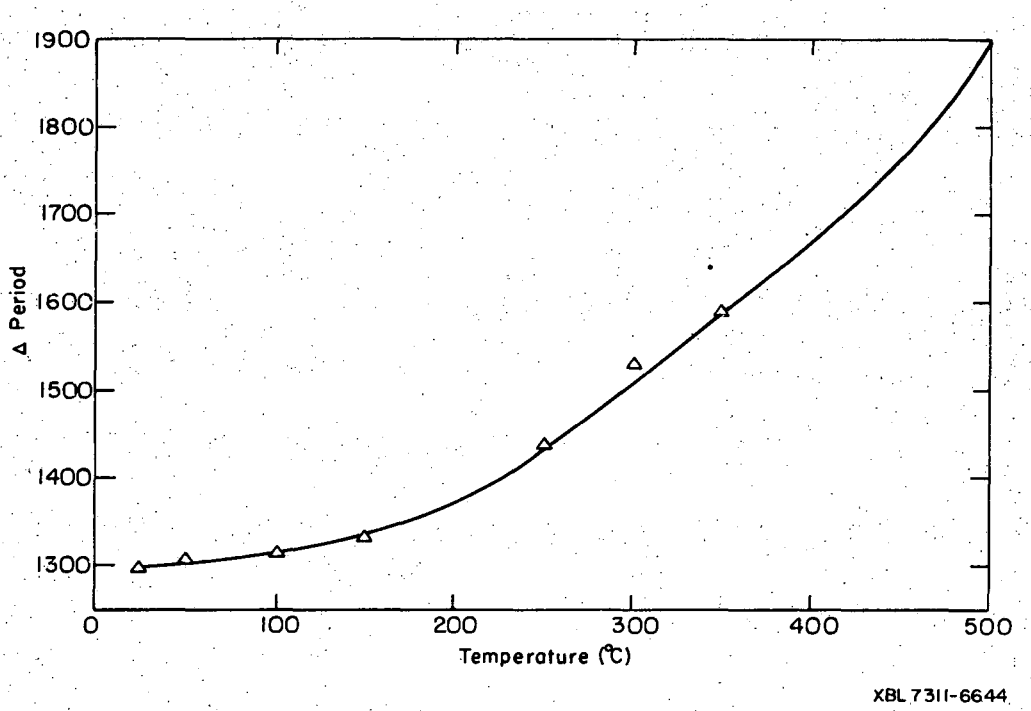

1900
1800
1700
1600
1500
1400
1300
Δ Period
0
100
200
300
400
500
Temperature (°C)
XBL 7311-6644

Fig. 6

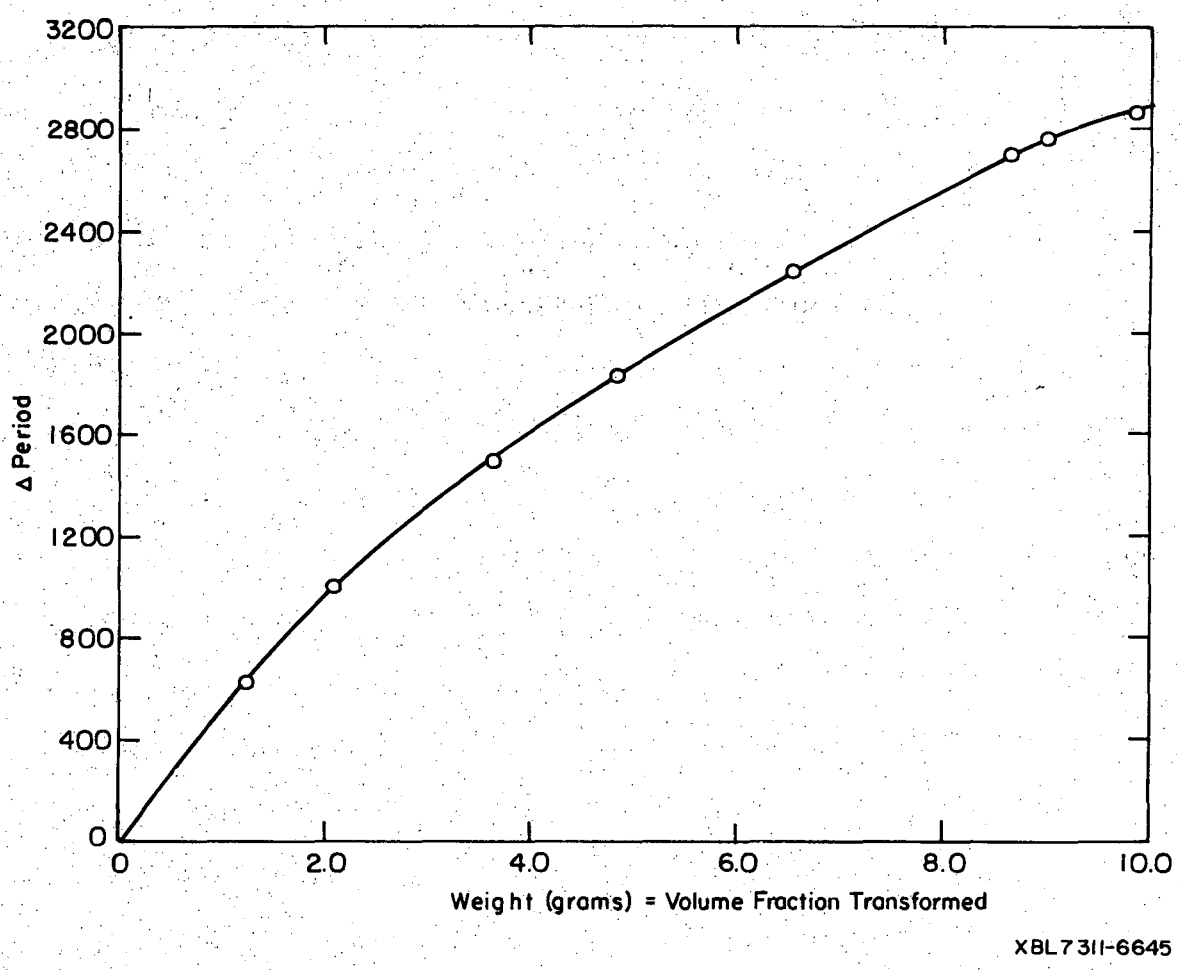

3200
2800
2400
2000
1600
1200
800
400
0
Δ Period
0
2.0
4.0
6.0
8.0
10.0
Weight (grams) = Volume Fraction Transformed
XBL7311-6645

Fig. 7

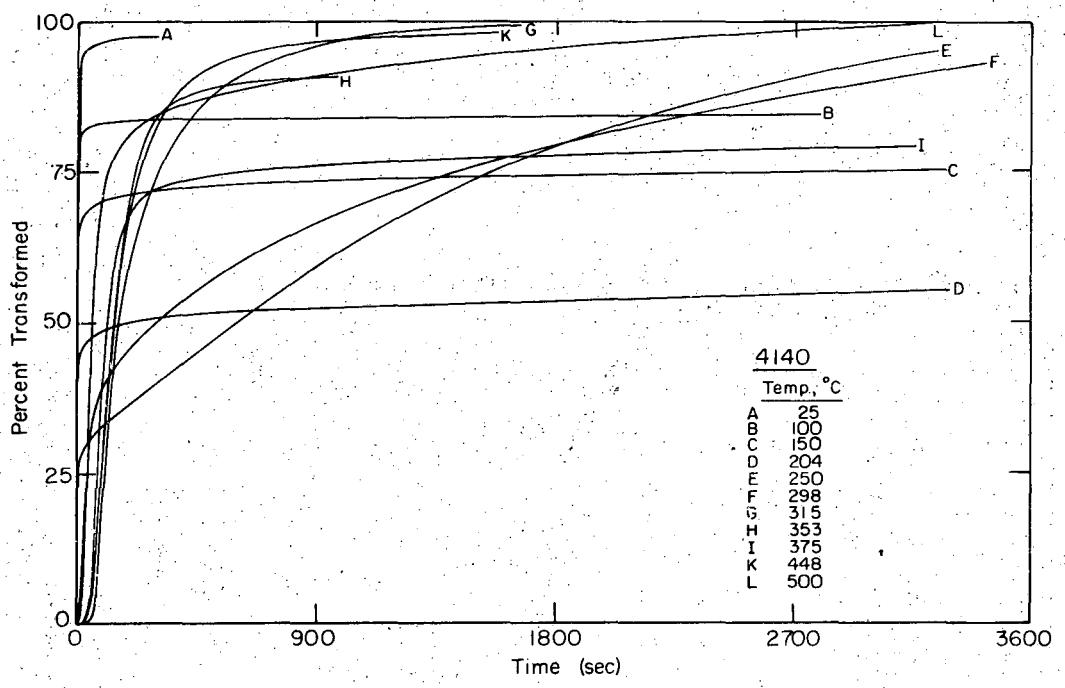

100
75
50
25
0
Percent Transformed
0
900
1800
2700
3600
Time (sec)
A
K
G
L
E
F
H
B
I
C
D
4140
Temp., °C
A 25
B 100
C 150
D 204
E 250
F 298
G 315
H 353
I 375
K 448
L 500

Fig. 8

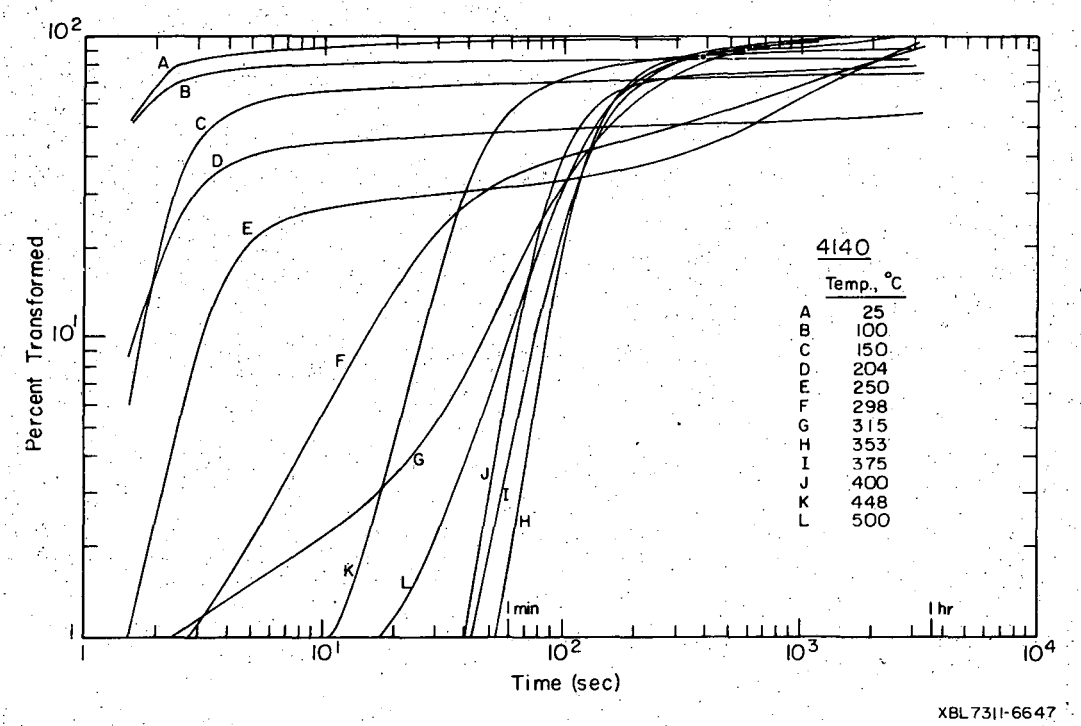

10^2
10^1
1
Percent Transformed
10^1
10^2
10^3
10^4
Time (sec)
1 min
1 hr
A
B
C
D
E
F
G
K
L
J
I
H
4140
Temp., °C
A 25
B 100
C 150
D 204
E 250
F 298
G 315
H 353
I 375
J 400
K 448
L 500
XBL 7311-6647

Fig. 9

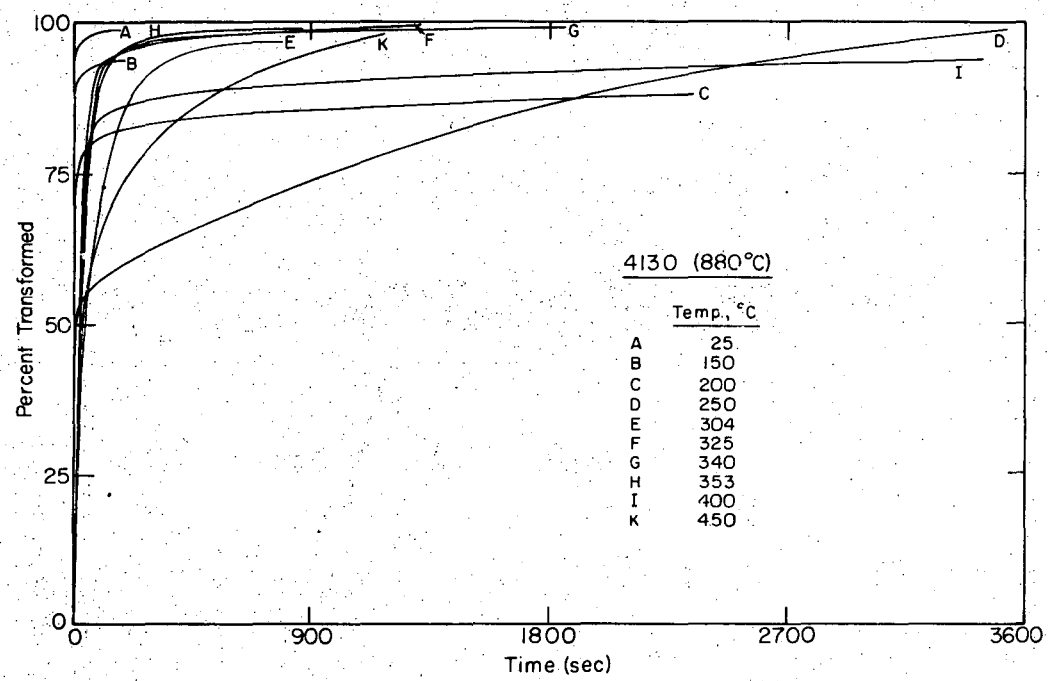

100
75
50
25
0
Percent Transformed
0
900
1800
2700
3600
Time (sec)
A
B
C
D
E
F
G
H
I
K
4130 (880°C)
Temp., °C
A 25
B 150
C 200
D 250
E 304
F 325
G 340
H 353
I 400
K 450

Fig. 10

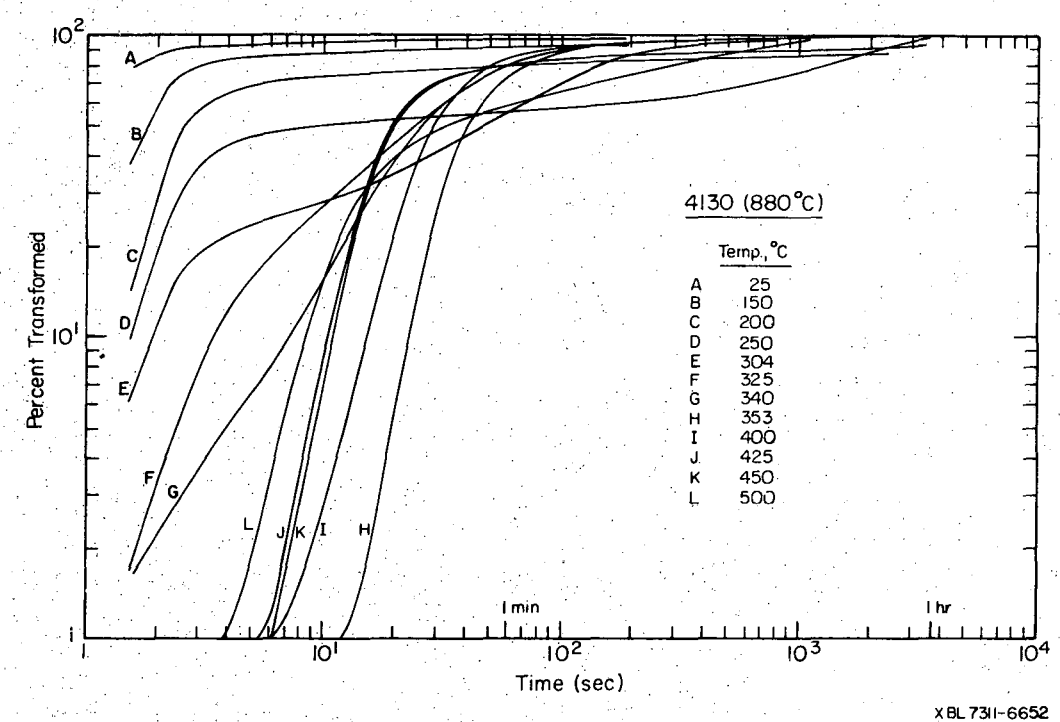

10^2
10^1
1
Percent Transformed
1
10^1
10^2
10^3
10^4
Time (sec)
1 min
1 hr
A
B
C
D
E
F
G
H
I
J
K
L
4130 (880°C)
Temp., °C
A 25
B 150
C 200
D 250
E 304
F 325
G 340
H 353
I 400
J 425
K 450
L 500
XBL 7311-6652

Fig. 11

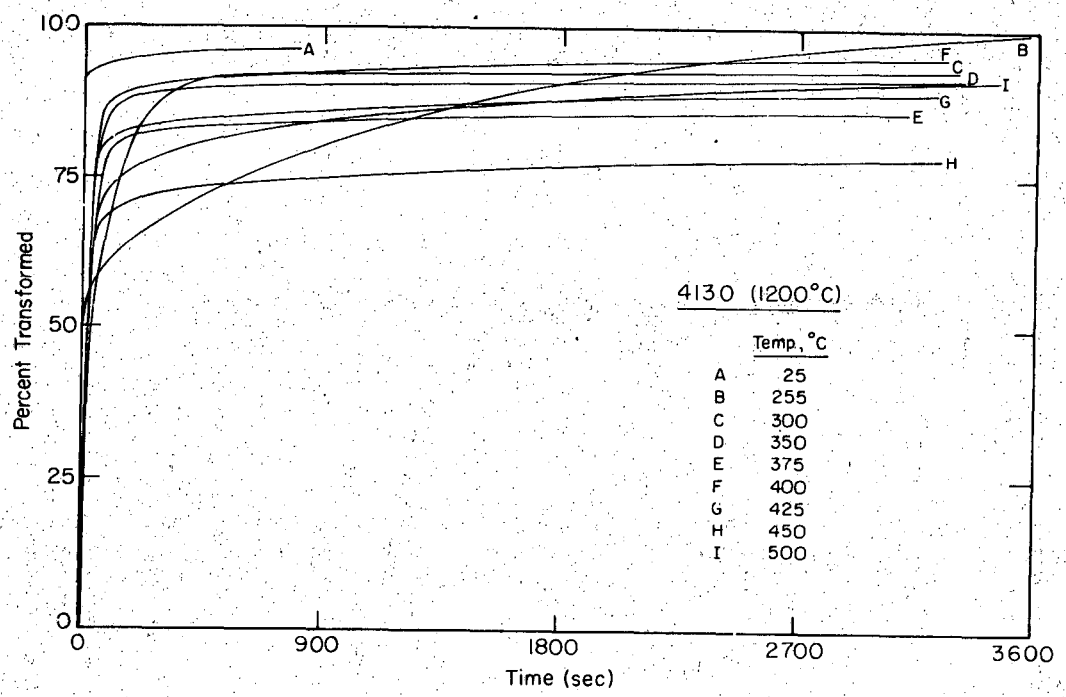

100
75
50
25
0
Percent Transformed
0
900
1800
2700
3600
Time (sec)
A
B
C
D
E
F
G
H
I
4130 (1200°C)
Temp, °C
A 25
B 255
C 300
D 350
E 375
F 400
G 425
H 450
I 500

Fig. 12

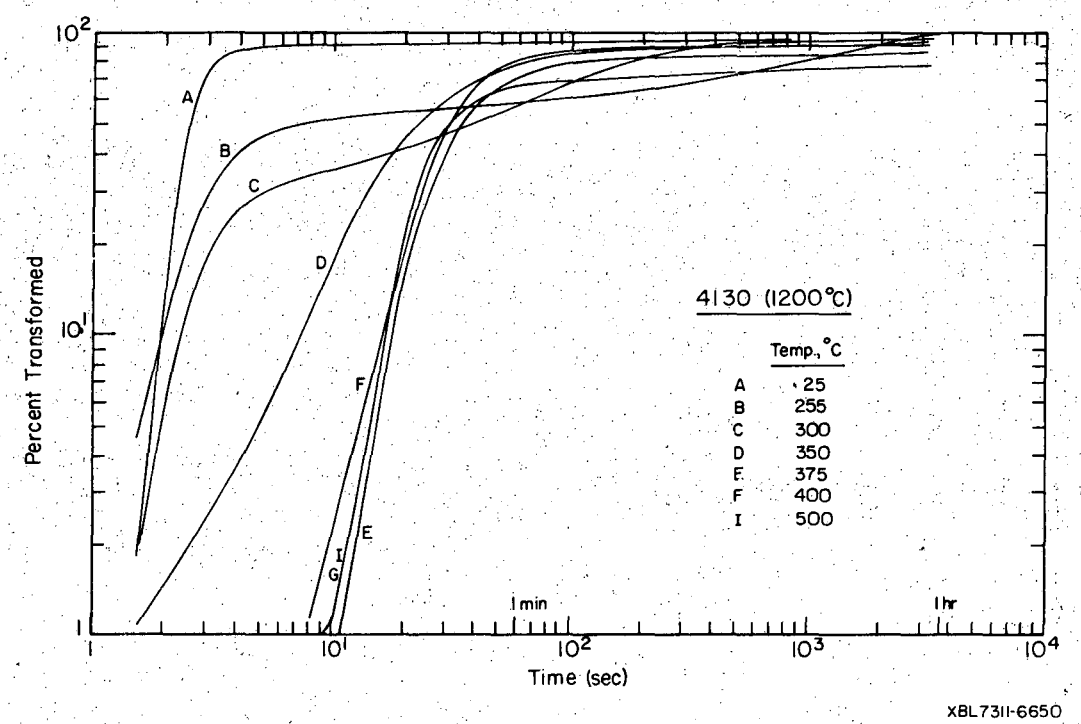

10^2
10^1
1
Percent Transformed
1
10^1
10^2
10^3
10^4
Time (sec)
1 min
1 hr
A
B
C
D
E
F
G
I
4130 (1200°C)
Temp, °C
A 25
B 255
C 300
D 350
E 375
F 400
I 500
XBL7311-6650

Fig. 13

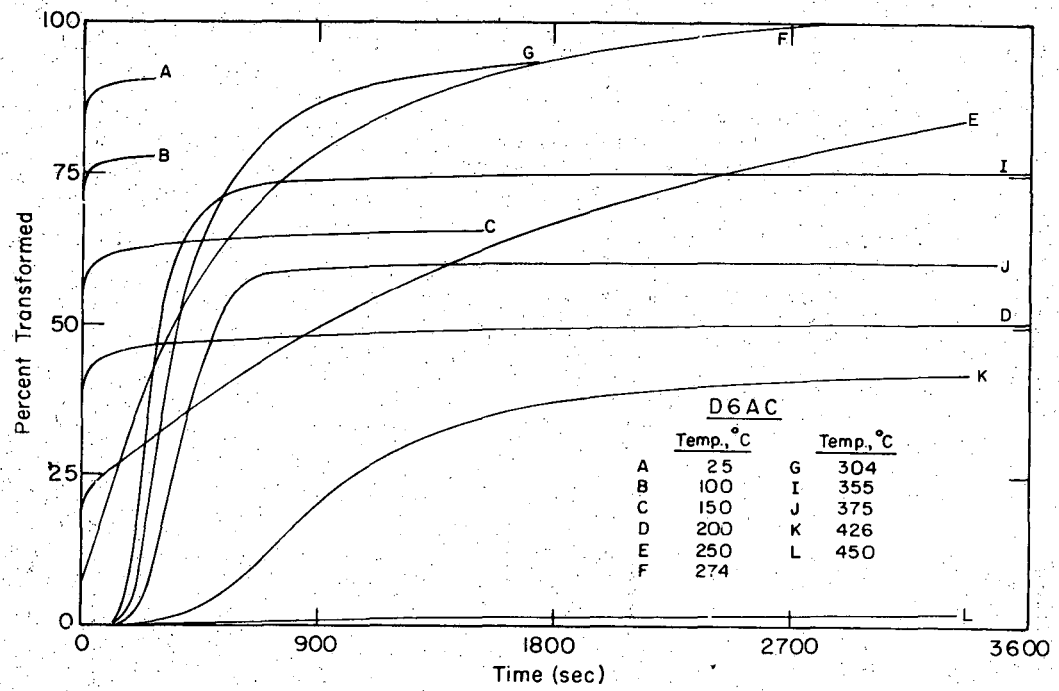

100
75
50
25
0
Percent Transformed
0
900
1800
2700
3600
Time (sec)
A
B
C
D
E
F
G
I
J
K
L
D6AC
Temp., °C
A 25
B 100
C 150
D 200
E 250
F 274
G 304
I 355
J 375
K 426
L 450

Fig. 14

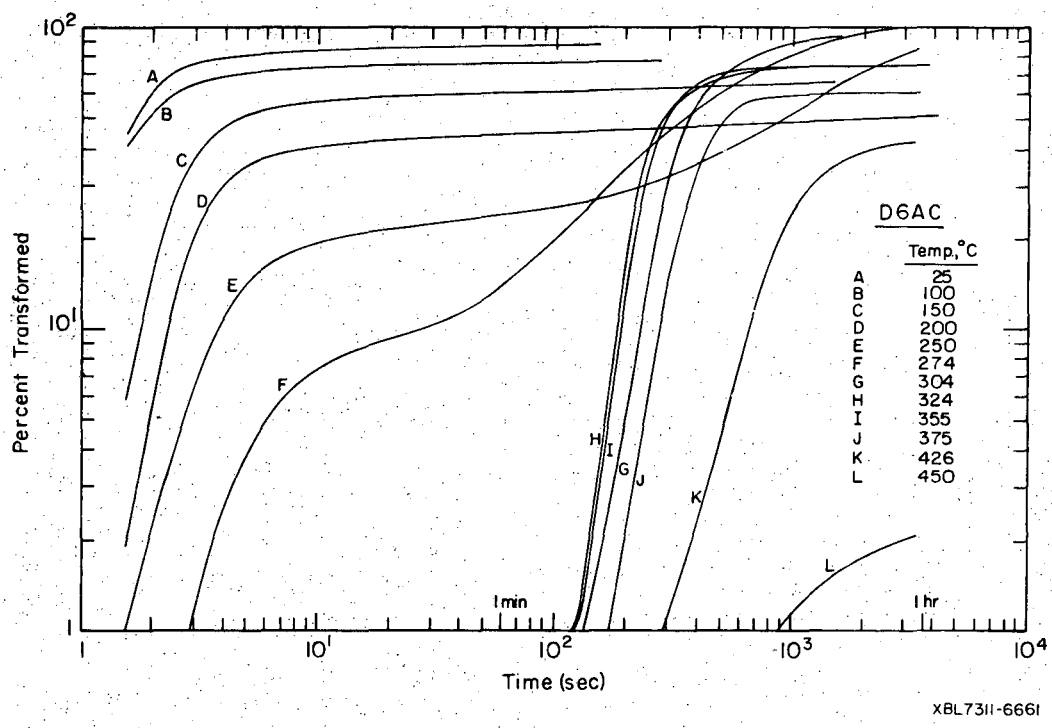

10^2
10^1
1
Percent Transformed
1
10^1
10^2
10^3
10^4
Time (sec)
1 min
1 hr
A
B
C
D
E
F
G
H
I
J
K
L
D6AC
Temp., °C
A 25
B 100
C 150
D 200
E 250
F 274
G 304
H 324
I 355
J 375
K 426
L 450
XBL7311-6661

Fig. 15

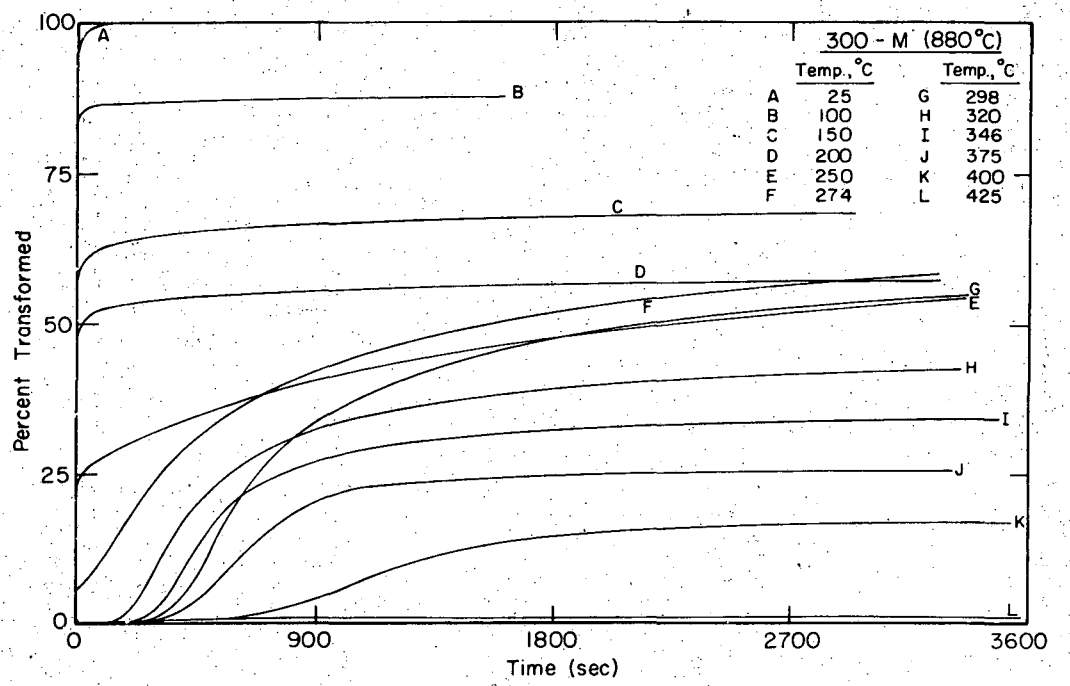

300 - M (880°C)
Temp., °C
Temp., °C
A 25
B 100
C 150
D 200
E 250
F 274
G 298
H 320
I 346
J 375
K 400
L 425
Percent Transformed
Time (sec)
0
25
50
75
100
900
1800
2700
3600

Fig. 16

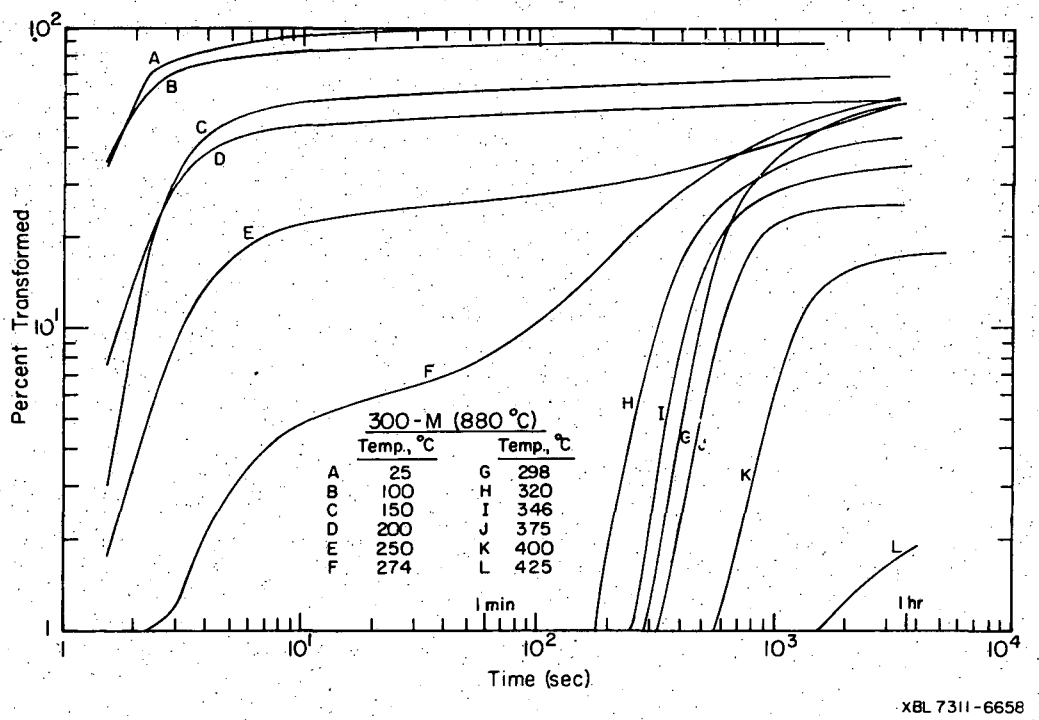

300-M (880 °C)
Temp., °C
Temp., °C
A 25
B 100
C 150
D 200
E 250
F 274
G 298
H 320
I 346
J 375
K 400
L 425
Percent Transformed
Time (sec)
1 min
1 hr
XBL 7311-6658

Fig. 17

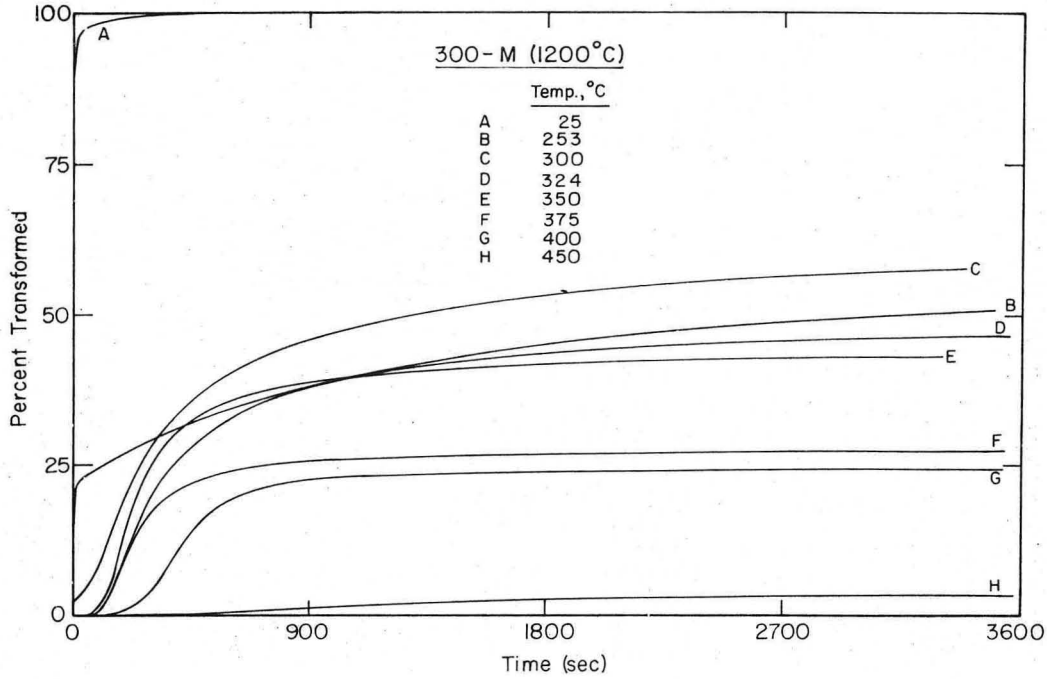

300-M (1200°C)
Temp., °C
A 25
B 253
C 300
D 324
E 350
F 375
G 400
H 450
Percent Transformed
Time (sec)
0
25
50
75
100
900
1800
2700
3600

Fig. 18

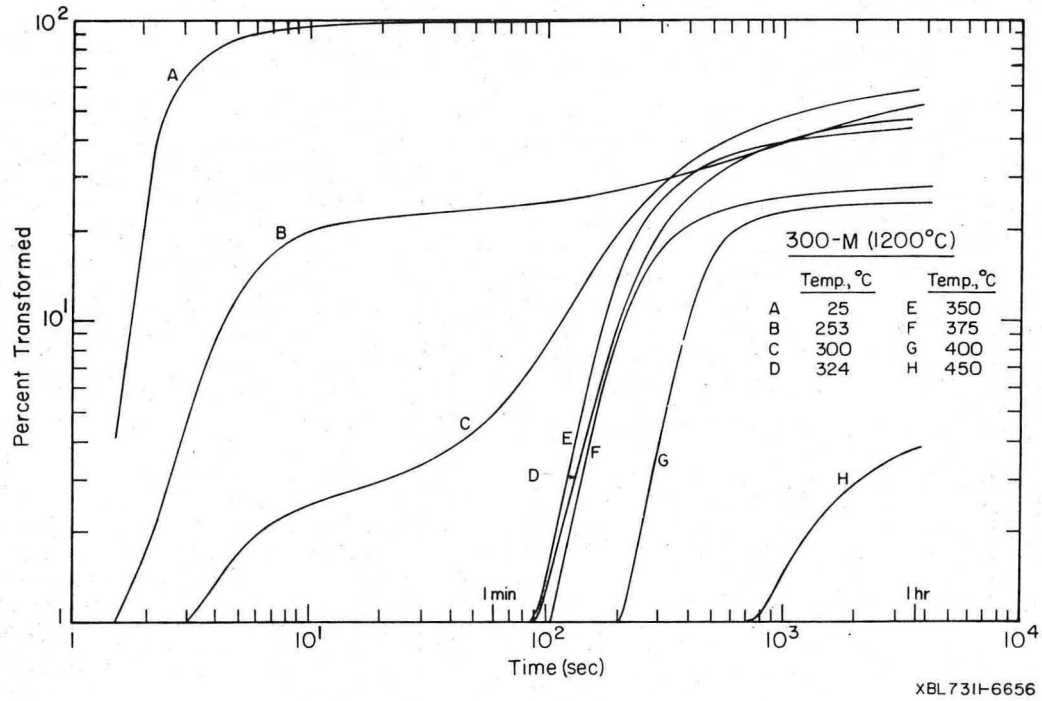

300-M (1200°C)
Temp., °C
A 25
B 253
C 300
D 324
Temp., °C
E 350
F 375
G 400
H 450
Percent Transformed
Time (sec)
1 min
1 hr
XBL 731-6656

Fig. 19

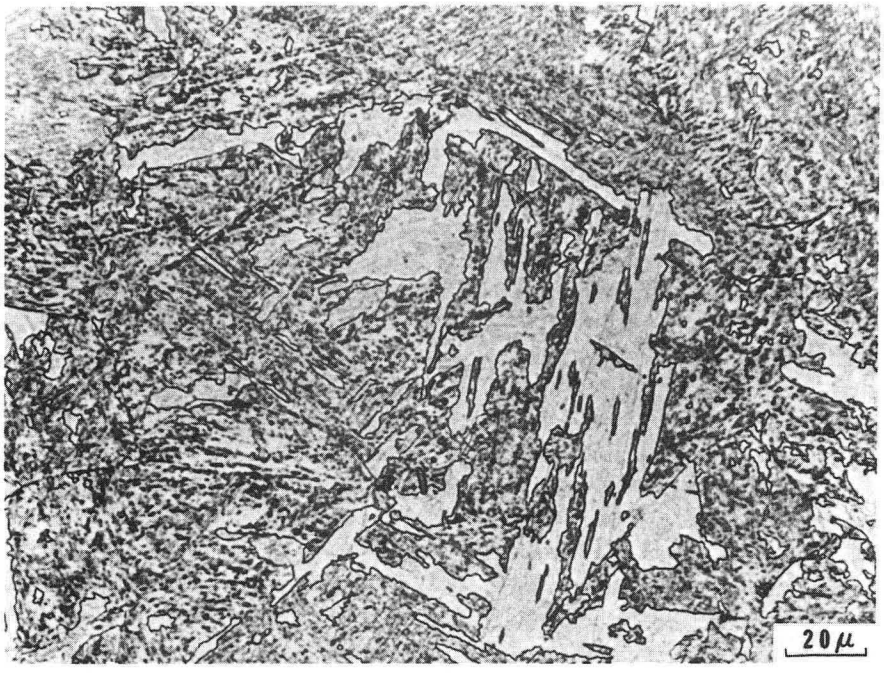
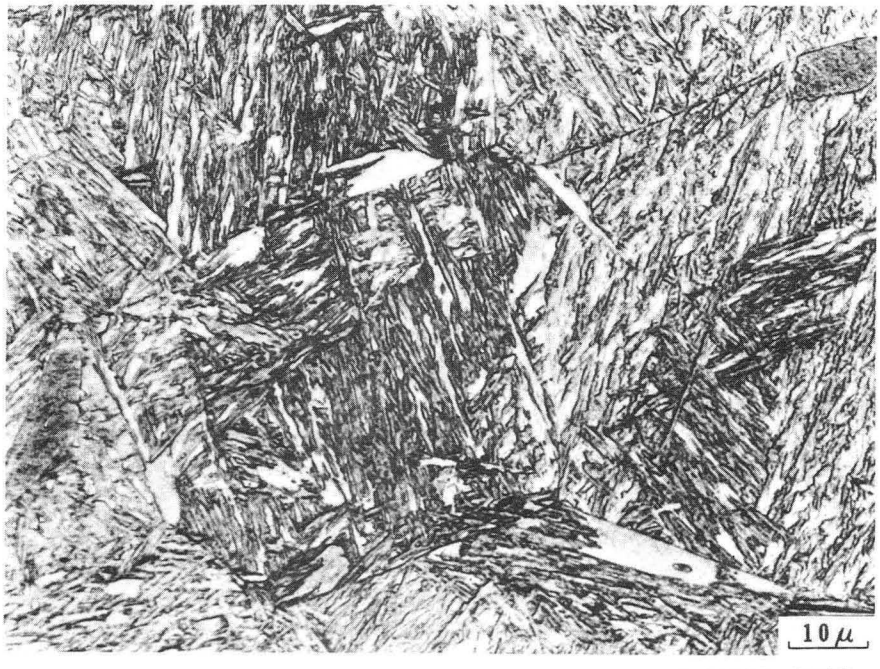


Fig. 20



XBB 7311-6707

Fig. 21

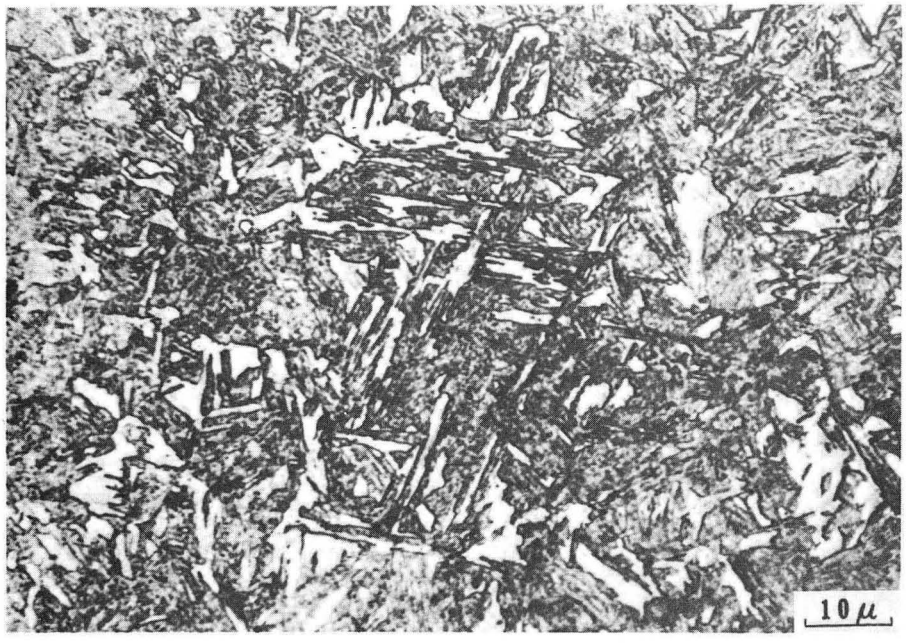
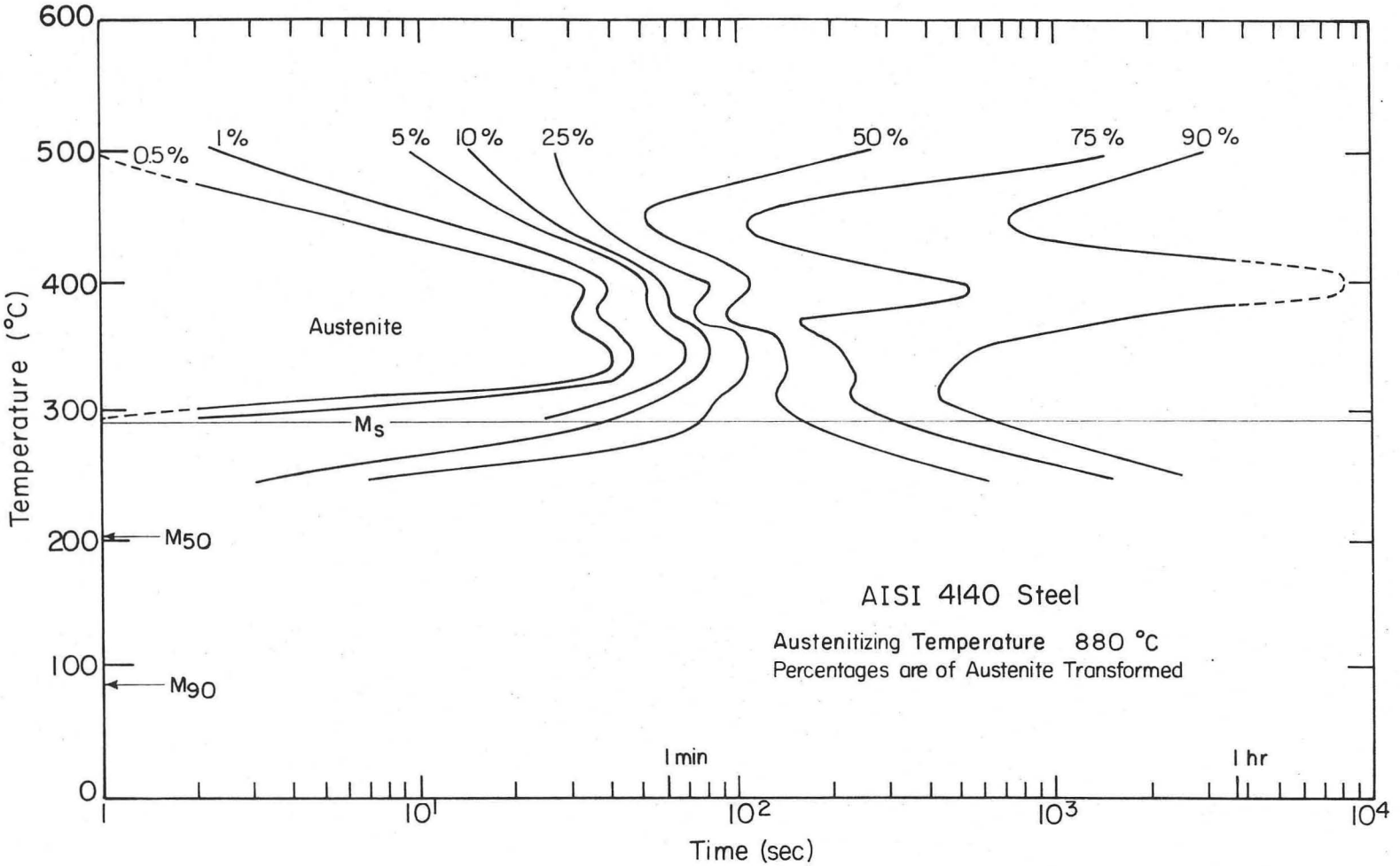


Fig. 22

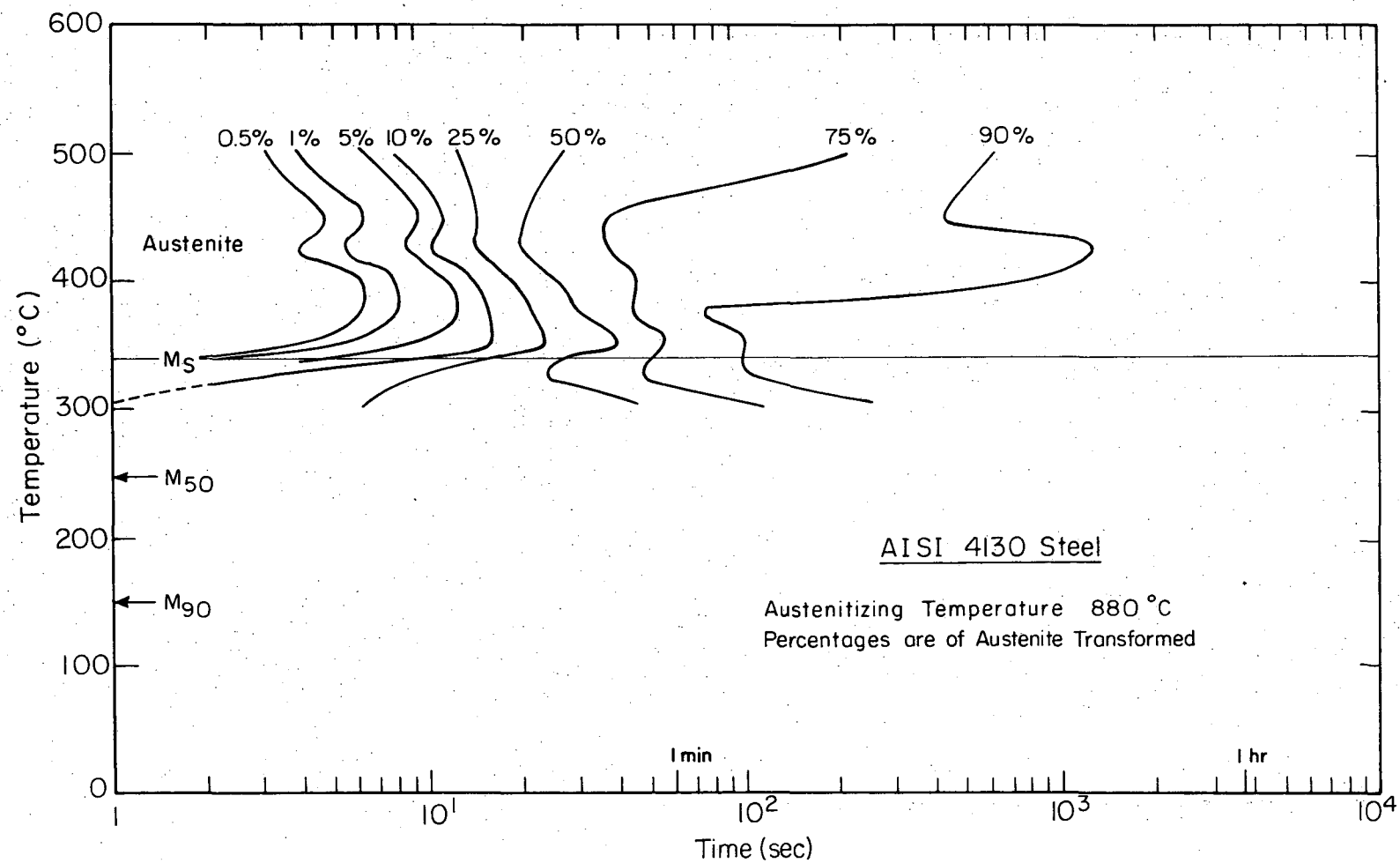
XBB 7311-6705

Fig. 23



XBL 7311-6648

Fig. 24



XBL 7311-6654

Fig. 25

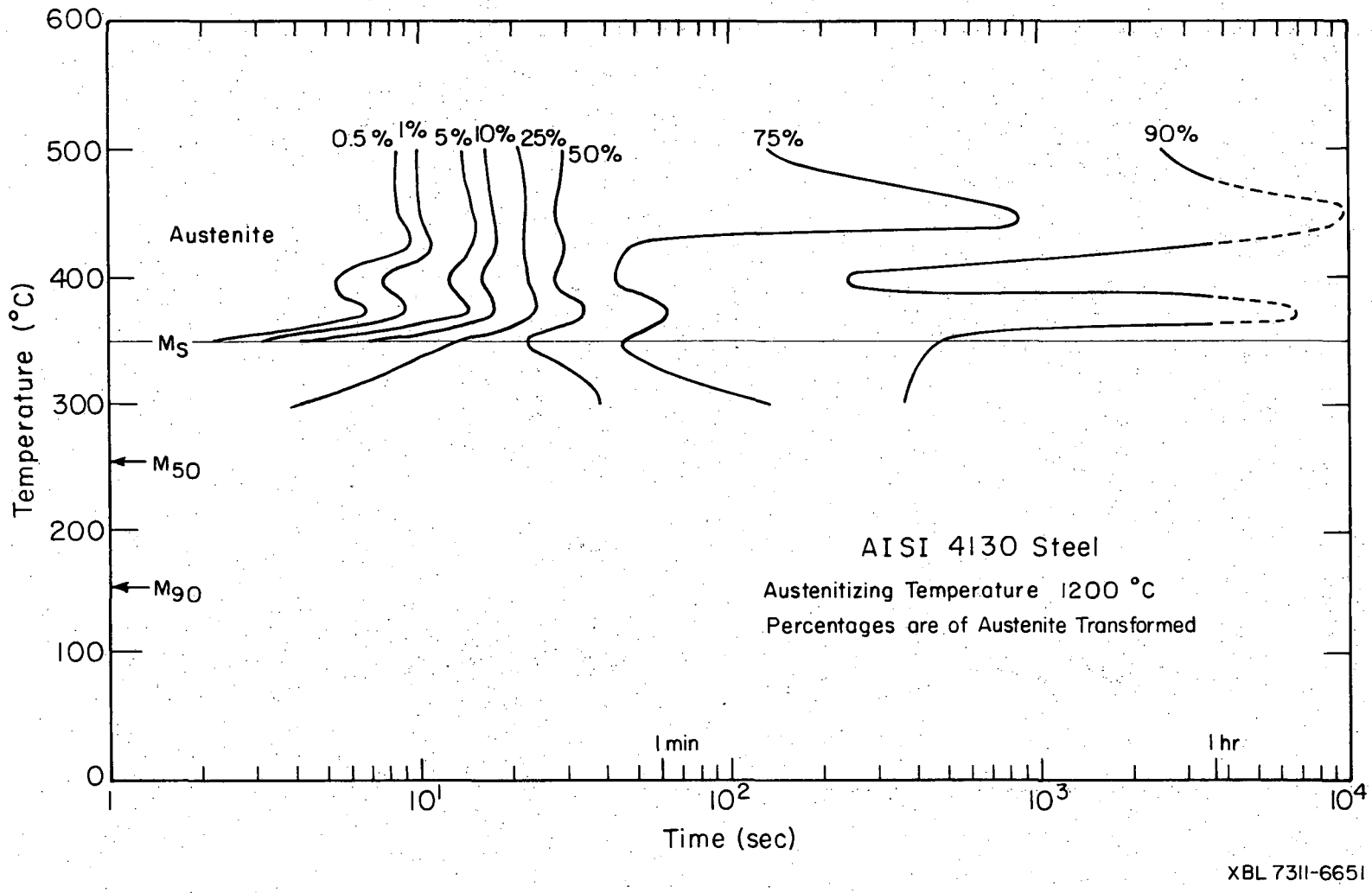

600
500
400
300
200
100
0
Temperature (°C)
0.5 %
1%
5%
10%
25%
50%
75%
90%
Austenite
Ms
M50
M90
AISI 4130 Steel
Austenitizing Temperature 1200 °C
Percentages are of Austenite Transformed
1 min
1 hr
1
10¹
10²
10³
10⁴
Time (sec)
XBL 7311-6651

Fig. 26

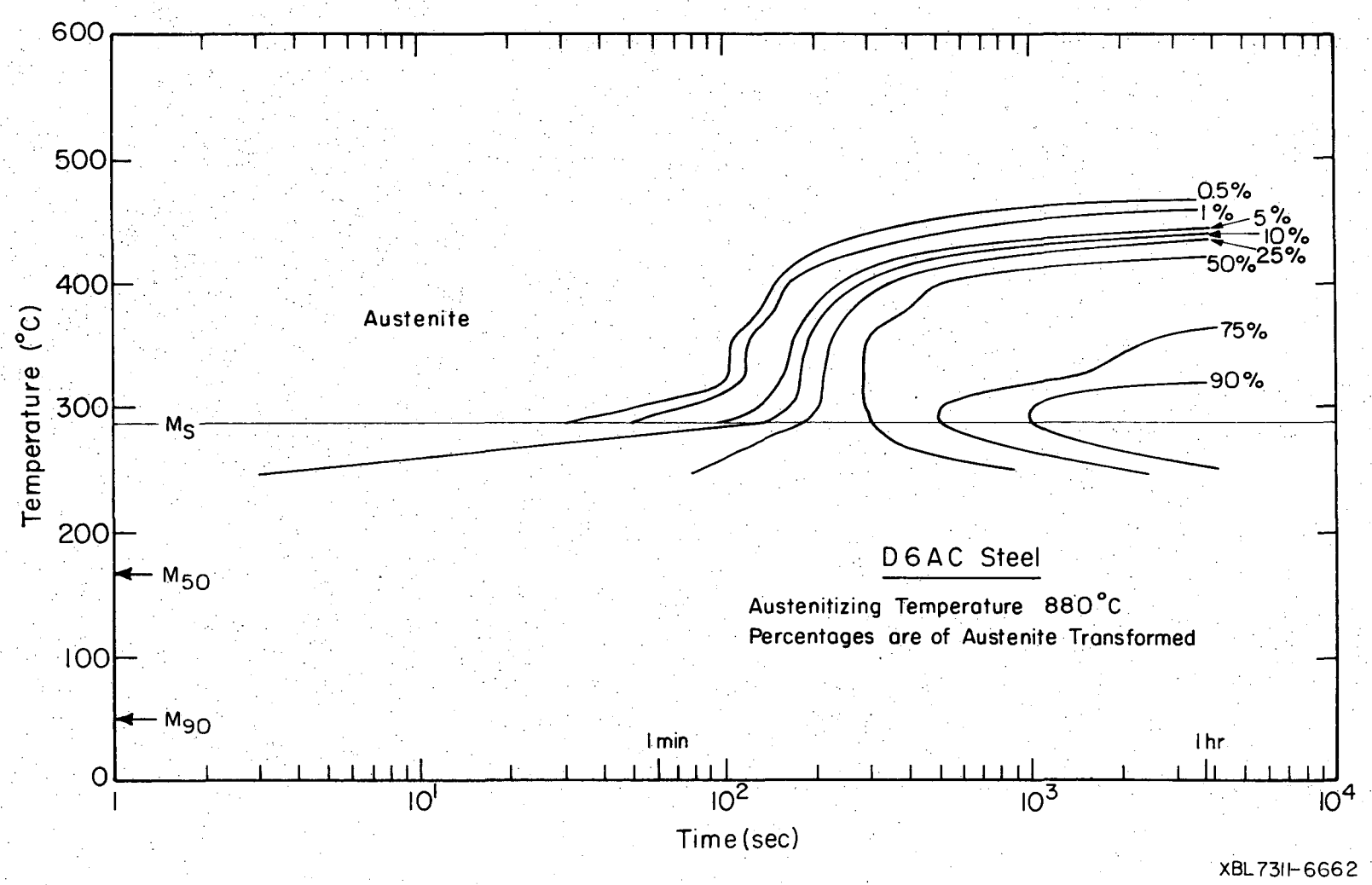

600
500
400
300
200
100
0
Temperature (°C)
Austenite
M_S
M_{50}
M_{90}
0.5%
1%
5%
10%
25%
50%
75%
90%
D6AC Steel
Austenitizing Temperature 880°C
Percentages are of Austenite Transformed
1 min
1 hr
1
10^1
10^2
10^3
10^4
Time (sec)
XBL 7311-6662

Fig. 27

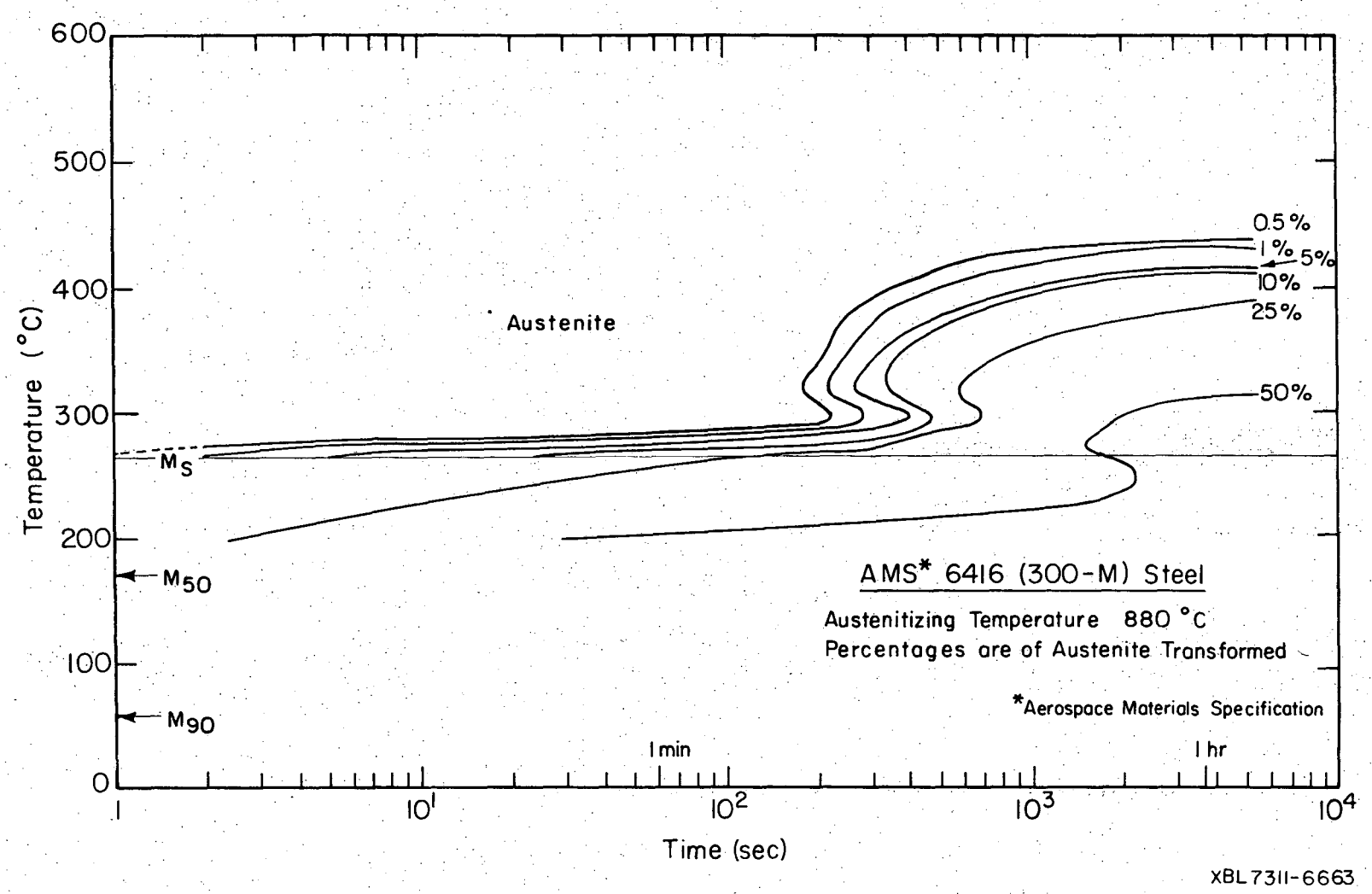
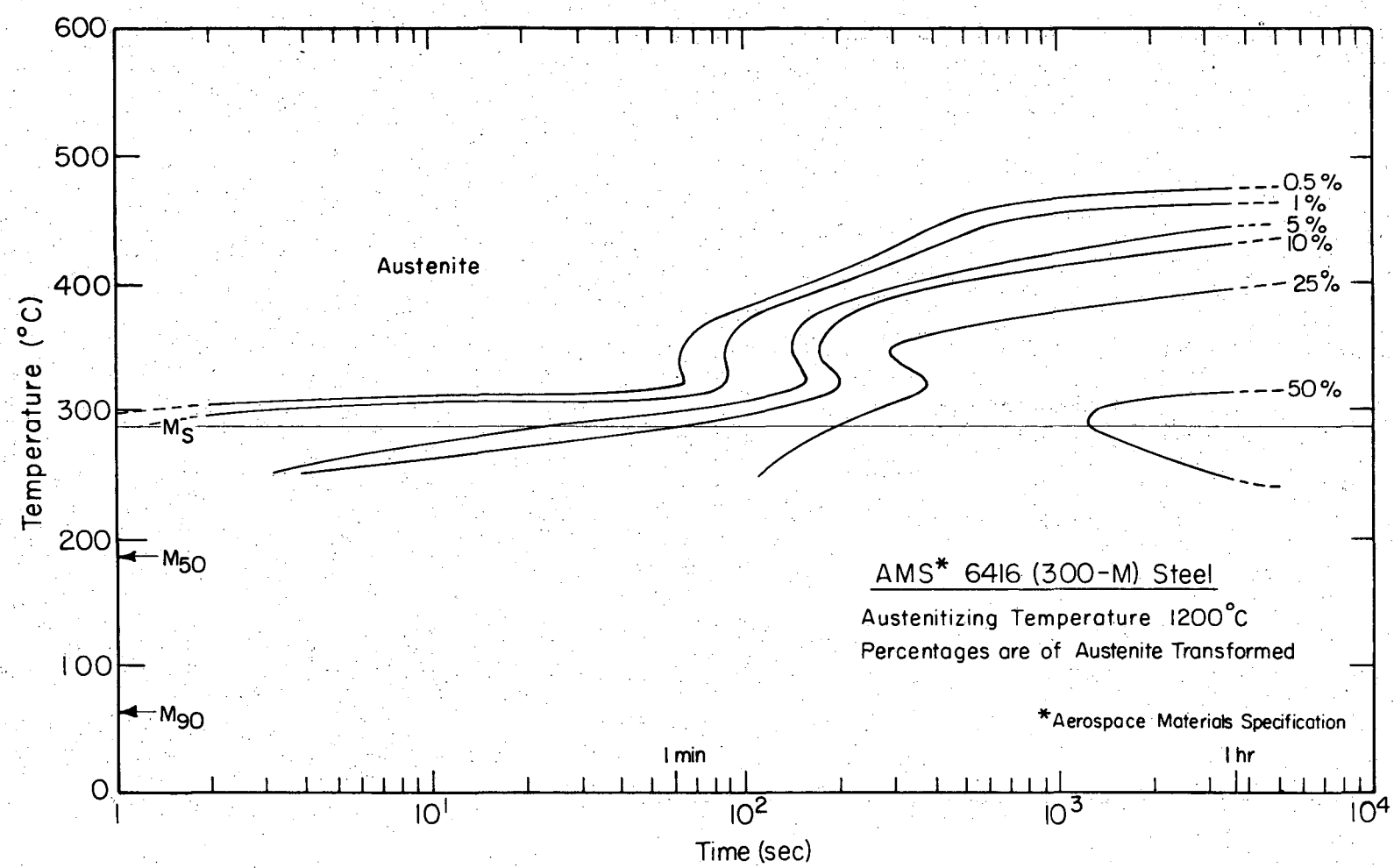

600
500
400
300
200
100
0
Temperature (°C)
Austenite
0.5%
1%
5%
10%
25%
50%
M_S
M_{50}
M_{90}
AMS* 6416 (300-M) Steel
Austenitizing Temperature 880 °C
Percentages are of Austenite Transformed
*Aerospace Materials Specification
1 min
1 hr
1
10^1
10^2
10^3
10^4
Time (sec)
XBL 7311-6663

Fig. 28



XBL 7311-6657

Fig. 29

Fig. 30

XBB 7311-6704

Fig. 31

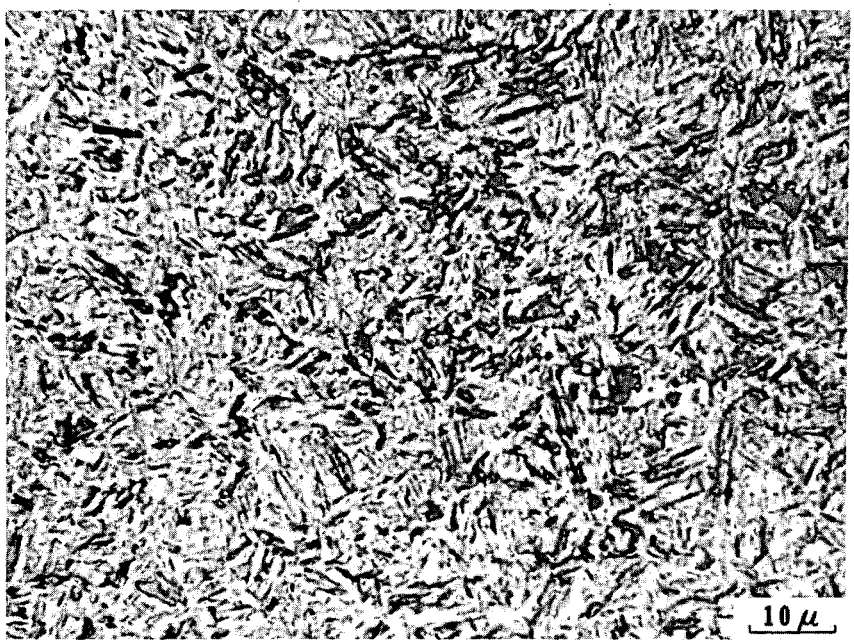
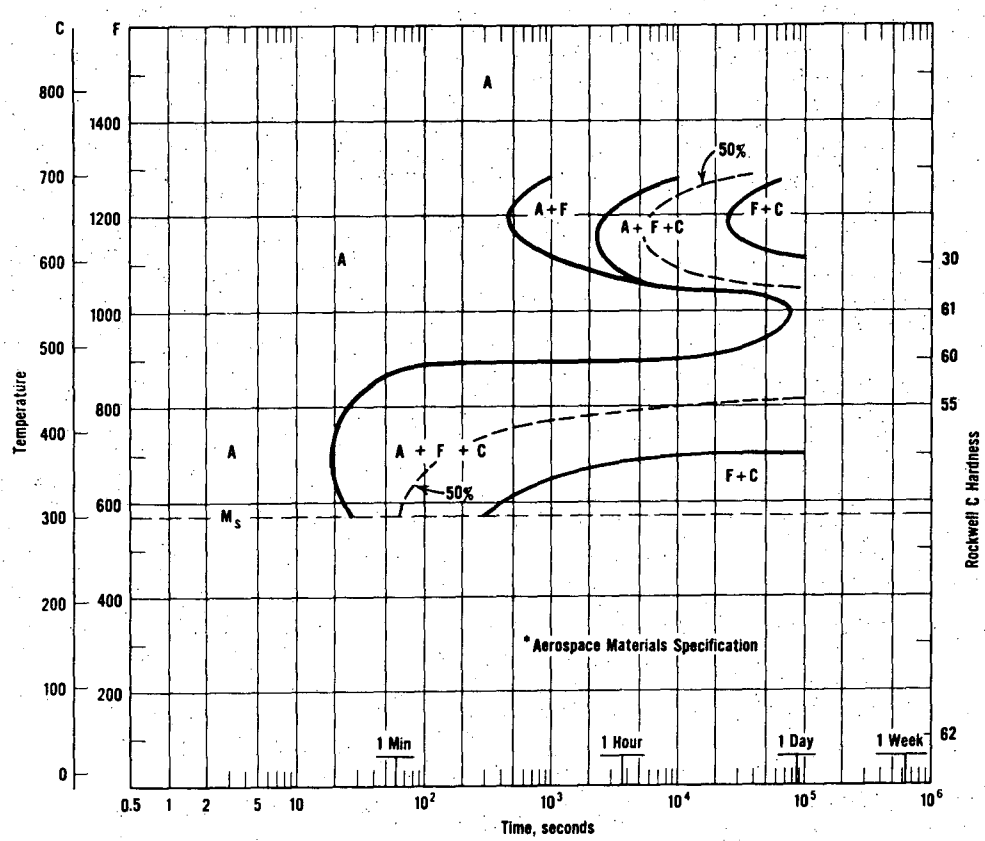


Fig. 32

XBB 7311-6706

Fig. 33



AMS* 6416 (300-M)

C-0.43 Mn-0.83
Si-1.55 Ni-1.84
Cr-0.91 Mo-0.40
V-0.12

Austenitized at 1575 F
Grain Size: 5-7

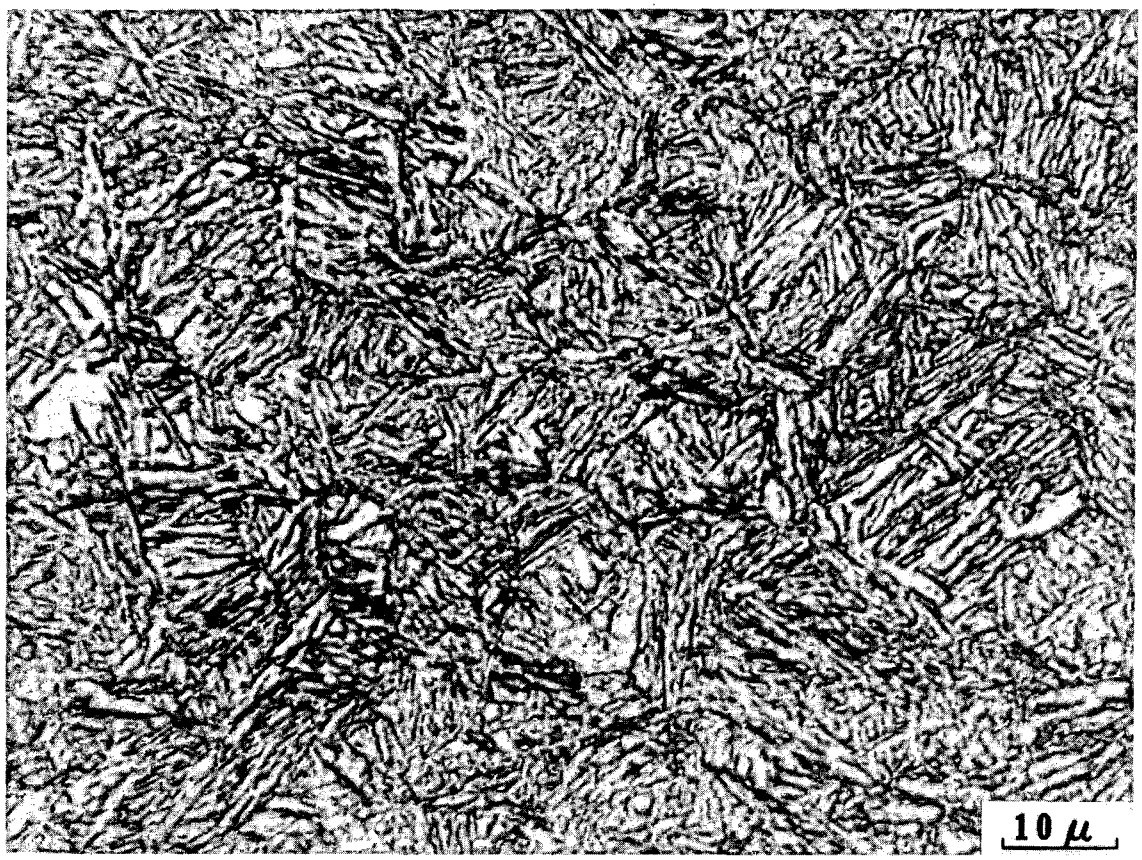
Starting Criterion:
0.5% Transformation

Legend
A = Austenite
F = Ferrite
C = Carbide
M = Martensite

Data from
Bethlehem Steel Co.

XBL 7310-5543

Fig. 34



XBB 7311-6708

Fig. 35

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