Spring 2009

# Quench factor analysis of wrought and cast aluminum alloys

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# QUENCH FACTOR ANALYSIS OF WROUGHT AND CAST ALUMINUM ALLOYS

by

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MATERIALS SCIENCE AND ENGINEERING

2009

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## ABSTRACT

Mechanical property variation across the cross section of heat treatable aluminum alloys is a major concern. To minimize such variation, a proper understanding of kinetic transformations and estimation of mechanical properties is required. The Jominy end quench test has been used successfully to study the effect of quench rate on the final heat treated properties of wrought and cast aluminum alloys. This test produces varying cooling rates along the length of a cylindrical sample cooled with water at one end.

Jominy bars of wrought and cast aluminum alloys were solutionized, end-quenched, and aged to T6 temper condition after delays of 1 hour and 120 hours. The hardness values were measured along the length of the Jominy bar. Previous studies have shown that the hardness along the length of the bar follows an Avrami relationship. The present work also measures hardness along the Jominy bar, and the data was used to determine the Avrami parameters (k,n) for various delays and heat treatments of alloys. The accuracy of the Avrami parameters was verified by plotting the calculated Avrami against the hardness data as a function of distance from the quenched end.

Mini tensile samples were then taken from specific locations on the Jominy bar. The experimental strength values and their Avrami fit were plotted as a function of distance from the quenched end. Strength values estimated from the Avrami fit were 95% accurate. This study allows prediction of strength at a given quench rate.

Finally, cooling curves were simulated at various points along the Jominy bar using FLUENT. Quench factors were calculated along the length of the bar. Using the cooling curves and the calculated quench factors, C-curves were generated for each alloy, and a specific heat treatment applied.

## ACKNOWLEDGEMENTS

I wish to express my deepest gratitude to my advisor, Dr. Joseph W. Newkirk for providing me with an opportunity to pursue a master's degree in Missouri University of Science and Technology. His enthusiasm and constant support have motivated me to successfully complete my research work. His suggestions, guidance and personal attention have been constant source of encouragement.

I would like to thank my committee members, Dr.Von L. Richards and Dr. Matthew J. O'Keefe for their time and effort . I would like to Dr. Rajiv Mishra for providing me the required equipment.

I would like to thank Anand Jambunathan and Jen Hsien Hsu for their continuous support. I would also like to thank the research group working for Dr. Rajiv Mishra in helping with the mini tensile samples testing.

Finally, I would like to thank my parents, brother and friends for their continuous support and care.

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# 1. INTRODUCTION

## 1.1. BACKGROUND

Aluminum and its alloys are characterized by low density, a good strength-to-weight ratio, excellent corrosion resistance, ease of fabrication, and reasonable cost. The strength can be increased by alloying, cold working, and precipitation hardening. These materials are now widely used in the automotive, aerospace, industry etc. For example, in automotive, cast aluminum alloys are replacing cast iron engine components for weight reduction, lower emissions, and fuel economy. At the same time, requirements for durability and reliability have increased. Parts such as cylinder heads and pistons, which are directly exposed to combustion, require excellent thermal fatigue resistance. Heat treatment of aluminum alloys provides a wide variety of choices for the final properties of the component. Wrought aluminum alloys are used in various industries, such as aircraft and bicycle manufacturing, food processing, chemical industry, etc. The properties of wrought alloys can be altered, and desired properties in the final product can be obtained by altering the heat treatment conditions.

## 1.2. PROBLEM STATEMENT

The aircraft industry typically uses forgings, which are expensive to design and produce. As an alternative to forgings, high speed machining of thick plates can be used. Property variations across the cross section are a major concern in the case of thick plates. To minimize the residual stresses developed during quenching, slow cooling rates can be used. However, slow cooling rates may impair mechanical properties. To minimize this problem, a better understanding of the kinetic transformations is required, and mechanical properties must be estimated from cooling data. Also, the effect of heat treatment on the properties of cast aluminum alloys is affected by the width of the sample sections. As the sample size increases, variations in thickness will complicate estimation of properties. A systematic approach is needed to obtain the mechanical properties of sample sections based on experimental data.

## 1.3. METHODOLOGY

The Jominy end quench (JEQ) test offers a method for studying many quenching conditions with a few samples. Cooling from one end gives a continuous range of quench rates, which can be used to compare cooling rates in geometry of a given part. The sample can be heat treated to a given set of conditions. This is a tremendous advantage over attempting the same study with individual samples. The bar has the same composition, the same solution heat treatment, the same aging time and the same aging temperature. The only variable is the quench rate. The JEQ has been successfully used to determine the effect of quench rate on the final heat treated properties of both wrought and cast aluminum alloys.

For this study, wrought aluminum alloys 7075 and 6061 and cast aluminum alloys A356 and B319 were solution treated, quenched, and aged to T6 temper condition. Based on previous work (discussed in detail in the forthcoming sections), hardness studies were carried out on wrought alloys using a Rockwell B scale and a Vickers hardness test with a 1 kg load for cast alloys. Hardness along the length of a Jominy bar follows an Avrami relationship. Hardness values were used to determine the Avrami constant k and the

Avrami exponent n. To predict tensile properties along the Jominy bar, mini tensile studies were performed on samples from various points along the Jominy bar.

Quench factor analysis was carried out using the hardness data, which was calculated as a function of distance from quenched end using the Avrami parameters. Thermocouple data was not used due to the amount of noise detected. Also, thermocouples could not be placed closely along the Jominy bar due to interference between two successive points. Based on these constraints, simulation was determined to be the best solution. Quench factors were calculated at various points, and time increments were calculated from the cooling curves simulated using FLUENT. The results were then used to calculate the critical times for transformation. Placing thermocouples at points that were used for quench factor calculations was not feasible, hence the JEQ test was simulated. The quench factors, time increments, and critical times for transformation form a set of non linear equations that were solved using MATLAB to determine the critical times

.

## 2. LITERATURE REVIEW

The major hardening mechanism in heat treatable aluminum alloys is precipitation hardening. Heat treatable alloys contain an amount of soluble alloying elements that exceeds the equilibrium solid solubility limit at room temperature. The amount present may be less or more than the maximum amount soluble at the eutectic temperature. The sample is heated to a temperature near the solidus so that all the hardening elements go into the solid solution. This operation is called "solution heat treating." The driving force for precipitation increases with the degree of supersaturation and, consequently, with decreasing temperature. The rate of precipitation also depends on atom mobility, which is reduced with decreasing temperature. The solid solution formed at higher temperature may be retained in a supersaturated state by cooling with sufficient rapidity (quenching) to minimize precipitation of solute atoms as coarse, incoherent particles. After quenching, controlled precipitation of fine particles at room temperature or elevated temperatures is used to develop the mechanical properties of the heat treated alloys.

Alloys may exhibit property changes at room temperature after quenching; this is called "natural aging." Precipitation can also be accelerated in the alloys by heating them above room temperature. This is called "artificial aging."

The changes that occur during precipitation are a complex sequence of time-dependent and temperature-dependent changes. At relatively low temperatures and during initial periods of artificial aging at moderately elevated temperatures, the principal change is a redistribution of solute atoms within the solid-solution lattice to form clusters or Guinier- Preston (GP) zones that are considerably enriched in solute. This segregation produces a distortion of lattice planes both within the zones and extending into a several atom layers into the matrix. With an increase in the number of zones, the degree of disturbance of the regularity and periodicity of the lattice increases. The strengthening effect of the zones results from additional interference with the motion of dislocations when they cut the GP zones.

When the aging time or temperature is increased, the zones are either converted into or replaced by particles having a crystal structure distinct from that of the solid solution and also different from the structure of the equilibrium phase. These are called as transition phases. They have a specific crystallographic orientation relationship with the solid solution, such that the two phases remain coherent on certain planes by adaption to the matrix through local elastic strain. Strengthening in this case is attributed to the impedance of the dislocation motion provided by the presence of lattice strains and precipitate particles. Strength increases as the size of precipitates increases, as long as the the dislocations continue to cut the precipitate.

The precipitation reaction produces further growth of the transition phase particles, with an increase in coherent strain, until the strength of the interfacial bond is exceeded and coherency disappears. This generally coincides with a change in the structure of the precipitate, from transition to equilibrium form. The strengthening mechanism in this case is caused by the stress required for the dislocation to loop around the precipitate, rather than by cutting the precipitate. Strength decreases with increasing size of the precipitate and increased interparticle spacing.

## 2.1 Al-Zn-Mg-Cu ALLOY SYSTEM

The alloys of Al-Zn-Mg-Cu, also known as 7XXX alloys, have the highest strength among all the commercial aluminum alloys and are among the most important heat treatable aluminum alloys. Zinc is the primary alloying element, followed by magnesium (2.1-2.9 wt %) and copper (1.2-2 wt %).

The characteristics of ternary aluminum-zinc-magnesium alloys are influenced by the high solid solubility of both the alloying elements. The phases in equilibrium with the aluminum matrix in commercial alloys are designated $MgZn_2$ (η-phase), $Mg_3Zn_3Al_2$ (T-phase), and $Mg_5Al_3$ (β-phase). The first phase ranges in composition from $MgZn_2$ to $Mg_4Zn_7Al$. The T-phase has a wide range of composition, from 74% zinc-16% magnesium to 20% zinc-31% magnesium. The β-phase generally occurs only when the magnesium content is considerably higher than the zinc content. Such alloys are strengthened by magnesium in the solid solution.

In quarternary alloys, the η-phase ranges from $MgZn_2$ to CuMgAl and may be described as Mg $(Zn,Al,Cu)_2$. The composition of the T-phase ranges from that of the aluminum-magnesium-zinc ternary to that of the phase designated $CuMg_4Al_6$; and may be described as $Mg_3$ $(Zn,Al,Cu)_5$. A third phase in commercial alloys is $CuMgAl_2$ (S-phase), which has a small range of composition. The $CuAl_2$ phase appears only if copper is considerably in excess of magnesium.

Schneider [1] examined the effect of alloying elements on the quench sensitivity. Quench sensitivity was defined in terms of quench rates and properties. The greater the decrease in properties as a function of quench rate, the greater the quench sensitivity. Studies showed that quench sensitivity decreases with increased Zn/Mg ratios. Alloys with high Zn/Mg ratios reduced supersaturation without affecting the age hardening capacity. The depth of hardening also increased with increasing Cu/Mg ratios. Polmear [2] studied the effect of 1-2% Cu additions on the aging characteristics of Al-Zn-Mg alloys. Hardness-aging time curves were developed for temperatures between -20$^{0}$C and 270$^{0}$C. The results showed that copper altered the precipitation process by accelerating the aging process. Copper also influenced the early stage of aging.

Mackenzie [3] studied quench rate and aging effects in Al-Zn-Mg-Cu aluminum alloys. The results showed that there are two critical quench rates for homogeneously distributed (precipitates developed in the matrix) and heterogeneously distributed (precipitates at high-angle grain boundaries and subgrain boundaries) precipitation. At cooling rates greater than 100$^{0}$C/sec, a completely homogeneously distributed phase occurs, and at cooling rates less than 100$^{0}$C/sec heterogeneously and homogeneously distributed precipitation occurs. Also, using the JEQ data, the relative amount of homogeneously distributed precipitate was found for 7075 and 7050 in the peak age condition and 7075 had more heterogeneously distributed precipitates. Natural aging response studies show that in the 7075 alloy the initial clustering was followed by formation and growth of GP zones, with no formation of $\eta$` observed. In 7050, clustering was observed followed by GP zone formation, and at long aging times, precipitation of $\eta$` occurred [3].

### 2.1.1. Effects of Processing Parameters

Many processing parameters affect the mechanical properties of aluminum alloys. These parameters include the chemical composition of the alloy, casting and homogenization methods, solution heat treatment, quenching, stretching, and aging. This work focuses on solution heat treatment, quenching, and aging processes.

**2.1.1.1 Solution Heat Treatment:** For most alloys, the temperature at which the maximum amount is soluble depends on the eutectic temperature. Also, the detrimental effects of overheating and partial melting must be avoided. A few alloys, such as 7075 and 7050, permit flexibility in the choice of a solution heat treatment. Because the solution heat treatment temperature is based on the equilibrium solvus and solidus temperature, in certain circumstances these alloys can exhibit incipient melting at temperatures far below the solidus.

In the case of wrought alloys, the time for the solution treatment increases with the thickness of the section. The rate of dissolution for a given particle size is the same at the solution treatment temperature regardless of the section thickness. The coarseness of the microstructure and the diffusion distances required to obtain a specific level of homogeneity must also be considered. For thin products, the time for solution treatment should be minimized to avoid excessive diffusion.

Increasing the solution heat-treating temperature from $350^{O}C$ to the limit of solubility, quenching, then artificially aging tends to improve the mechanical properties of the alloy. After the solubility limit is reached, increasing the solution treatment temperature accelerates aging [10] and increases hardness [11]. The effect of time at the solution treatment temperature has been studied extensively [12] [13]. Studies show that in case of wrought alloys there is little benefit in increasing the time at solution treatment temperatures. The values indicated in handbooks or product specifications are to ensure that a finished product with a given heat treating load reaches the process temperature.

Increased time can result in oxidation, blisters, and impairment of mechanical properties due to grain growth [14].

**2.1.1.2 Quenching:** Quenching and its cooling effect have been extensively studied [39][40]. The first systematic approach to correlate properties to quench rate in Al-Zn-Mg-Cu alloys was performed by Fink and Wiley [38] for thin (0.064") sheets. They determined that the maximum strength and corrosion resistance were obtained at quench rates exceeding 450$^{o}$C/sec. At intermediate quench rates of 450 to 100$^{o}$C/sec., strength was lower (using same aging treatment), but corrosion resistance was unaffected. Between 100$^{o}$C/sec and 20$^{o}$C/sec, strength decreased rapidly and corrosion resistance was minimized. At quench rates below 20$^{o}$C/sec, strength decreased rapidly, but corrosion resistance improved.

In general, high strength and high toughness materials have a higher quenching rate. Nevertheless, the distortion, warping, and development of residual stress in the materials with higher quenching rates must also be considered when choosing the quenching rate. The maximum attainable quench rate decreases with an increase in the section thickness.

**2.1.1.3 Aging:** Aging is the final heat treatment step necessary to attain required properties in the alloy. The process is complex and requires an understanding of vacancies, interaction of precipitates, and metastable phases.

The effect of precipitation on mechanical properties is accelerated by reheating the quenched material to a temperature of 90$^{O}$C to 200$^{O}$C. The characteristic feature of elevated temperature aging is the increase in tensile properties, especially yield strength, tensile strength, and toughness. Overaging decreases both tensile and yield strength, but the recovery of ductility is not in proportion to the loss of strength.

A naturally aged alloy can be heated for a few minutes to a temperature in the artificial aging range to attain the workability of freshly quenched material. Nevertheless, these effects are temporary, and the material begins to age naturally once it returns to room temperature. This process has been attributed to differences in the rate at which materials are heated to the overaging temperature, and this temperature in turn affects the width of the precipitation free zones at grain boundaries [43]. Since all the heat treatable alloys over-age with extended heating, the decrease in strength with time must be considered in selection of alloys and tempers for parts that operate at elevated temperatures.

In Al-Zn-Mg-Cu alloys, the sequence of precipitation occurs by clustering of vacancies, formation of GP zones, nucleation of η`, precipitation of η, and finally coarsening of precipitates. Vacancy rich clusters (VRC) are produced by quenching from GP zones [36][37]. Both GP zones and VRCs with a critical solute concentration are η` nucleation sites [15].

Two stages of GP zone formation have been found [16]. The kinetics of the first stage can be described by Cottrell-Bilby [17] kinetics, in which vacancy migration to dislocations is governed by diffusion. Duration of this stage depends on the aging temperature and the composition of the alloy. It was once thought that the formation of GP zones starts when Zn atoms cluster and are then joined by Mg atoms. Nuclei of the zones start forming on these clusters at a rate controlled by the diffusion of Mg atoms and by the diffusion of vacancies attached to solute atoms.

In the second stage, the GP zones grow, and the growth is slowed by the formation of coherency strains around them and by a decrease in supersaturation. In Al-Mg-Zn-Cu alloys, several phases have been identified that occur as a function of the precipitation sequence. These phases are as follows:

$$\alpha_{SSS} \Rightarrow S$$
$$\alpha_{SSS} \Rightarrow T' \Rightarrow T$$
$$\alpha_{SSS} \Rightarrow VRC \Rightarrow GPZ \Rightarrow \eta' \Rightarrow \eta$$
$$\alpha_{SSS} \Rightarrow \eta$$

In the first precipitation sequence, the S phase, $AlCu_2Mg$, is precipitated directly from the supersaturated solid solution ($\alpha_{SSS}$). In the second sequence, an intermediate phase T' occurs in the dissolution of solid solution, and ultimately the equilibrium T phase ($Mg_3Zn_3Al_2$) is formed. In the third precipitation sequence, the supersaturated solid solution decomposes to form VRCs, GP zones, intermediate η' phase, and equilibrium η ($MgZn_2$). Finally, in the fourth sequence, the equilibrium phase η forms from the supersaturated solid solution directly.

## 2.2. Al-Mg-Si ALLOY SYSTEM

This alloy system forms another important class of heat treatable aluminum alloys known as 6XXX alloys. The general characteristics of this alloy system have moderately high strength (≈ 310 MPa), relatively low quench sensitivity, and good corrosion resistance. The equilibrium phase diagram of this system is well established. The system is pseudobinary Al-$Mg_2Si$ at a magnesium-to-silicon ratio of 1.73:1 (wt%). The pseudobinary system has an eutectic at 595$^{0}$C. The composition of the eutectic liquid is 8.15 wt% of magnesium and 4.75 wt% of silicon in equilibrium with an aluminum solid solution containing 1.13 wt% of magnesium and 0.67 wt% of silicon. When the system is thus divided, the aluminum rich-end can be considered to comprise two simple ternary systems, Al-$Mg_2Al_3$-$Mg_2Si$ at 450$^{O}$C and Al-Si-$Mg_2Si$ at 555$^{O}$C. Excess silicon and magnesium reduce the solid solubility of $Mg_2Si$ in aluminum, although the effect of magnesium is more predominant than that of silicon.

Pashley et al.[4] studied the precipitation sequence in this alloy system. This sequence is as follows:

Supersaturated solid solution→ semicoherent β" rods // $<001>_{Al}$→semicoherent β' needles // $<001>_{Al}$→semicoherent β plates // $<001>_{Al}$→ noncoherent β$Mg_2Si$.

These Al-$Mg_2Si$ alloys can be divided into three categories. The first category has a total amount of magnesium and silicon less than 1.5%. These alloys are in a nearly balanced ratio or have excess silicon. A good example of this type of alloy is Al 6063 which is mainly used in extruded architectural sections and contains 1.1% $Mg_2Si$. With a solution treatment temperature of just above 500$^{O}$C and low quench sensitivity, this alloy does not require separate solution treatment after extrusion; however, these alloys may be air quenched and artificially aged to obtain moderate strength, good ductility, and excellent corrosion resistance.

The second category of alloys contains 1.5% or more of magnesium and silicon. The addition of other elements, such as 0.3% Cu, increases the strength in a T6 temper condition. Manganese, chromium, and zirconium additions control the grain structure. Alloys such as 6061, which belong to this category generally, have a tensile strength of 310 MPa, whereas the previous category of alloys (6063) has a tensile strength of only 240 MPa in the T6 temper condition. Also, these alloys require a higher solutionizing temperature than the first category of alloys and are quench sensitive. Therefore, they require a solution treatment process followed by rapid quenching and artificial aging.

The third category of alloys contains almost the same amount of $Mg_2Si$, but they have excess silicon. In an alloy containing 0.8% $Mg_2Si$, the addition of 0.2% excess silicon increases the strength by 70 MPa; without the addition, tensile strength is only 230 MPa. Nevertheless, large amounts of excess silicon are less beneficial. These alloys have a grain boundary fracture in recrystallized structures due to segregation of excess silicon to the grain boundary. The effect of excess silicon can be counteracted by the addition of manganese, chromium, or zirconium, preventing recrystallization during heat treatment. Common alloys of this group are Al 6351 and Al 6009.

### 2.2.1 Effects of Processing Parameters

**2.2.1.1 Solution Heat Treatment:** Highly alloyed 6061 has an excess of $Mg_2Si$ at the solution heat treating temperature; therefore, slow cooling results in a Widmanstatten form. Solution treated 6061 cannot have distinguished microstructures in the T4 and T6 temper and requires special techniques for distinction. Some of the 6XXX alloys used for electrical conductivity applications are put in an overaged condition, and when etched they exhibit a light band along the grain boundaries caused by precipitate free zones.

**2.2.1.2 Quenching:** As discussed above, the highest strength, and most often the greatest corrosion resistance, is obtained with fast quenching rates. Water (mixed with ethylene glycol) is the most widely used and efficient quenching medium. The bath should be of sufficient volume to ensure that boiling does not take place during quenching. If desired, the temperature of the water can be maintained by additives that decrease the surface tension or form film on the hot metal.

**2.2.1.3 Aging:** The precipitation hardening temperature range is similar for alloys of 2014 and 6061. Recommended commercial treatments for T6 temper were selected for this work on the basis of experience with many production lots, representing an optimum compromise for high strengths, good production control, and operating economy. Some paint bake operations are in the temperature range commonly used for artificial aging. Consequently, auto body sheet can be formed in the T4 temper where formability is high, and then it can be aged to higher strengths during the paint bake cycle. Alloy 6010 was developed to maximize the response to aging in the temperature used for paint baking.

## 2.3. CAST ALUMINUM ALLOYS

The mechanical properties of cast aluminum alloys depend on the casting process and also the heat treatment of the alloy. T.Takaai et al. [5] studied the effect of heat treatment on certain mechanical properties of cast A356 alloy, including fracture toughness. Various studies have been carried out on A356 aluminum alloy to examine the relationship among heat treatment parameters such as solutionizing temperature, aging temperature, and aging time, and to evaluate their effect on mechanical properties and microstructure. Solutionizing and aging at relatively high temperatures promoted sufficient precipitations and spherodization of the eutectic silicon structure, increasing yield stress and the fracture strength.

Boileau et al. [6] studied the effects of solidification time and heat treatment on tensile and fatigue properties of cast 319 aluminum alloy. The solidification time showed a significant effect on the microstructure, in particular on the secondary dendrite arm spacing and the distribution of porosity. The study proved that the aging behavior of heat treatable cast aluminum alloys depends on the cooling rate following solution treatment, since a softer material is obtained if the cooling rate decreases. G.E Byczynski et al. [7] showed that a three-stage process is required to optimize the mechanical properties of cast aluminum alloys, ensure dimensional stability, and prevent mechanical property change during use. The first step is solution treatment, in which the material is heated to a temperature very close to the eutectic temperature so that the hardening constituents (secondary phases) go into solid solution. In the second step, quenching slows the precipitation of hardening constituents from the solid solution. In the final step, the material is aged at room or elevated temperatures to obtain the desired mechanical properties. Studies have shown that the mechanical properties are independent of the aging cycle, but affected by the aging temperature and aging time [7].

Mehta [8] studied the quench sensitivity of cast aluminum alloys A356 and B319 using the JEQ. He found that hardness of the aged specimens was affected by the rate of cooling from solution treatment temperature. He also noted that the aging behavior of a heat treatable cast alloy has been found to depend on the cooling rate following the solution treatment, resulting in a softer material when the rate decreases. It demonstrated, too, that a signal-to-noise ratio of 15-30 was attainable using the Vickers hardness test with a 1kg load. The variability was determined by taking the standard deviation for each test block. The range of measurements was determined and divided by the standard deviation to yield the signal-to-noise ratio.

Mohammadi [9] studied the heat treatment effects on properties and structures of A356 and B319 cast aluminum alloys. He found that the Avrami coefficients for A356 and B319 JEQ bars after various heat treatment cycles were determined by fitting a trend curve to the hardness values. His work showed that the precipitates would have $n \approx 2$ suggesting a 2-dimensional diffusion path and disk shaped precipitates. Effects of sand casting versus permanent mold casting were investigated using design of experiment matrices for both A356 and B319. Mohammadi's work proved that the maximum hardness value of A356 alloys was dependent on aging time, aging temperature, and the interaction between quench delay and solidification rate. In the case of B319 alloys, the maximum hardness was dependent on aging time, solution time, and solution temperature. For A356 alloys the minimum hardness value was dependent on the aging time and temperature, whereas for B319 alloys it was dependent on aging time and solution time. The optimization of heat treatment cycles showed that increasing aging time or aging temperature increases the maximum hardness. With a decrease in aging time, the depth of hardness increases for A356 alloys, and the difference between maximum and minimum hardness decreases. For B319 alloys, a decrease in the aging time increases maximum hardness, and a decrease in solution time reduces both maximum hardness and the difference between maximum and minimum hardness. This effect may be due to insufficient time for the secondary phases (hardening constituents) to go into the solid solution. His work also developed the heat treatment properties for obtaining maximum surface hardness, proper depth of thickness and to minimize the quench sensitivity. The heat treatment in case of A356 was same for both permanent and sand castings where as in the case of B319 the solution treatment time is higher and the delay before aging is longer for sand castings. The artificial aging time in permanent mold castings is higher than sand cast alloys.

### 2.3.1 Effects of Processing Parameters

The time required for the solution heat treatment depends on the type of alloy, the fabrication method, and the thickness, all of which can influence the microstructure. These factors establish the proportions of solute that go into the solution and the size and amount of the distributed phases. Sand castings are generally held for 12 hours, whereas the permanent mold castings may require only eight hours because of their finer structure.

## 2.4. USE OF JOMINY END QUENCH TEST

The effect of alloying elements on the hardenability of steels has been widely studied using the JEQ test. Fewer studies have been published on the use of this technique for studying the quench rate effects of Al alloy systems.

Jominy and Boegehold [20][21] first described the end quench process in steels using a cylindrical steel sample 100 mm high and 25 mm in diameter. The specimen was austenized in a furnace, removed, then quenched in a specialized fixture with a vertical stream of water from one end. Cooling in the JEQ test can be approximated as one-dimensional and was proved to be invariant with the composition of steel. Nevertheless, the resulting hardenability is a function of the composition and grain size of the steel. The simple specimen design and the ease of the process have made this a popular method for measuring hardenability.

Loring, Baer, and Carlton [22] published the first paper on the use of the JEQ test to study aluminum alloys using a modified L-type specimen to obtain a wide range of cooling rates. The cooling curves were measured up to 25 mm, and hardness was measured using Rockwell B, F, and Vickers (5kg) scales. The study showed that higher quench rates yield decreasing hardness (in the as-quenched condition). The increase in hardness from the quenched end was consistently found to plateau at the depth of conical section in the L-type specimen. Low cooling rates produced relatively small changes in hardness.

‘tHart, et al.[23][24] studied extruded rods of 2024 and 7075 aluminum alloys using the JEQ technique. The bars were aged to 2024-T4, 2024-T6, and 7075-T73 conditions. They were then evaluated using a transmission electron microscope (TEM) and stress corrosion cracking (SCC) testing to observe the correlation among quench rate, corrosion properties, and microstructure. Vickers hardness tests were taken at 5 mm intervals. The 7075 alloy was found to be strongly quench sensitive, and hardness increases were found only in the first 60mm of the bar. Also, results showed that 7075-T6 was prone to SCC in the first 40 mm of the bar and was resistant at distances greater than 40 mm.

Hecker [25] used a similar apparatus to evaluate the aging cycles as a function of time for an Al-Mg-Si alloy and as an alloying addition to Al-Zn-Mg-Cu alloy. He proved that silicon has a significant effect on the age hardening characteristics of Al-Zn-Mg-Cu alloys by increasing the incubation time before initial hardening.

Various end quenching techniques similar to the JEQ have been developed. Bomas [26] used a rectangular specimen 15 mm x 140 mm x 300 mm, with the 15 mm x 140 mm face exposed to the quenching medium to measure the time-temperature-property diagram of an Al-Zn-Mg alloy. This arrangement exposed the specimen to a one dimensional heat transfer condition similar to that observed in the JEQ test. Tensile specimens were obtained at various points perpendicular to the axis of the quench medium, resulting in tensile properties dependent on the cooling rate. Using an apparatus similar to that of designed by Bomas, Arthur et al. [27] developed models of the build-up of residual stresses during the quenching process in various Al alloys. He modeled heat conduction and mechanical properties at high temperatures using constitutive equations.

Hergat [28] reported the steps necessary to achieve a ±1 HRC (hardness on Rockwell C scale) precision when the JEQ test is peformed on steels. His work offered a means to ensure that the machined flats are parallel, and that the operator error induced during hardness testing was reduced by use of semi-automatic machines. The specimen should be in a fixture so that the indenter may be accurately positioned and the sample firmly held. The fixture should clamp the specimen so that there is no deflection when the load is applied.

'tHart [23] determined experimentally that the free height of the water did not influence the cooling rates. This conclusion, however, is contrary to standard specifications ASTM A255 and SAE J406c, which fix the free height of the water at 65 mm.

Newkirk and Mackenzie [29] developed an efficient method of using the JEQ test on nonferrous alloys. Specimens made from extruded rods of 7075-T6 and 7050-T7451 were solution heat treated, quenched, and artificially aged. This work shaped a new understanding of the complex response of nonferrous alloys to processing conditions, especially quenching. It showed that 7075 is more quench sensitive than 7050, but the inflection points on the hardness curves are nearly identical.

Wei [30] studied the quench effect on properties of Al-Zn-Mg-Cu alloys. His work showed that the hardness distribution follows an Avrami relationship, with an Avrami exponent of 4 in the case of 7075 and 7050 aluminum alloys. Tensile studies used a plate end quench sample. The tensile bars were cut such that the longitudinal direction of the bar was parallel to the bottom edge of the plate. The ultimate tensile strength (UTS), yield strength (YS), and the percent of elongation decreased as the quench rate decreased. In the case of notched bar samples, the strength at fracture decreased with quench rate. The main drawback of this work was the unavailability of all the points in the test matrix. This study also showed that excessive first stage aging time results in reduced strength, whereas prolonged aging results in increased ductility due to a more uniform microstructure and more evenly distributed dispersoids.

## 2.5. QUENCH FACTOR ANALYSIS

Historically, quench rates have been used to predict properties [31][32][33] and microstructure after quenching. However, average quench rates are not sufficient to provide accurate property data or serve as a predictive tool. The quench factor was developed to predict properties quantitatively. The quench factor depends on the rate of precipitation during quenching. The kinetics of precipitation are assumed to follow an Avrami relationship [34].

$$V_f = 1 - \exp(-k\tau)^n \qquad (2\text{-}1)$$

where $V_f$ is the volume fraction that has been transformed, k is an Avrami constant related to critical time for nucleation and growth, $\tau$ is the quench factor, n is the Avrami exponent, and k is defined as:

$$k = k_0 e^{\frac{-Q}{RT}} \qquad (2\text{-}2)$$

where Q is the activation energy for transformation, T is the temperature ( $^{O}$K), and R is the gas constant. The fraction transformed, $V_f$, is expressed as [35]:

$$V_f = \frac{\rho(t) - \rho_i}{\rho_f - \rho_i} \qquad (2\text{-}3)$$

where ρ is the property measured, and the subscripts indicate either the final or initial value of the property.

If hardness is the property to be measured, and equation (2-3) is rearranged after substitution of equation (2-1), the hardness at any point x can be determined from the quenched end of a Jominy bar by:

$$H(x) = H_{max} - \Delta H(1 - \exp(-kx)^n) \qquad (2\text{-}4)$$

where $H_{max}$ is the maximum hardness ( the final hardness), ΔH is the difference between maximum and minimum hardness, k is the Avrami constant (a complex factor of nucleation times and quench rate), and n is the Avrami exponent.

The quench factor τ is defined as:

$$\tau = \int \frac{dt}{C_t} \qquad (2\text{-}5)$$

where τ is the quench factor, t is the time in seconds, and $C_t$ is the critical time. The collection of $C_t$ points is known as the C-curve. In general, the $C_t$ function is described as [41]:

$$C_t = K_1 K_2 \left( \exp \frac{K_3 K_4^{\ 2}}{RT(K_4 - T)^2} \right) \exp\left( \frac{K_5}{RT} \right) \qquad (2\text{-}6)$$

where $C_t$ is the critical time required for the precipitation of a constant amount of solute, $K_1$ is the amount of solute transformed during quenching, $K_2$ is the constant related to the reciprocal of the number of nucleation sites, $K_3$ is the constant related to energy required to form a nucleus, $K_4$ is the constant related to solvus temperature, $K_5$ is the constant related to activation energy for diffusion, R is the universal gas constant, and T is the temperature in Kelvin.

Equation (2-5) can be written as

$$\tau = \frac{\Delta t_1}{C_1} + \frac{\Delta t_2}{C_2} + ...... + \frac{\Delta t_n}{C_n} \tag{2-7}$$

where $C_1, C_2, ......C_n$ are the critical times of the C-curve, and $\Delta t_1, \Delta t_2 .....\Delta t_n$ are the incremental times described by the cooling curves. The predicted property can be described as a function of the quench factor:

$$P = P_{\min} + (P_{\max} - P_{\min}) \exp(k_1 \tau) \tag{2-8}$$

where P is the predicted property, $P_{max}$ is the maximum property, $P_{min}$ is the minimum property, $k_1$ is ln(0.995)=-0.00501, and $\tau$ is the quench factor.

Certain difficulties are associated with this method. First, the specific quench path must be known, which is difficult to measure and requires specialized equipment. The C-curve must also be known with sufficient precision. The lack of information regarding the C-curve limits the application of the quench factor.

The JEQ test provides a method to determine the quench factor and the C-curve. For a specific set of processing conditions, the quench factor can be determined by the JEQ test for multiple quench rates, using a single specimen.

The quench factor can be calculated by rearranging equation (2-8):

$$\tau = \frac{1}{K_1} \ln\left( \frac{(P - P_{\min})}{(P_{\max} - P_{\min})} \right) \tag{2-9}$$

A single JEQ test generates multiple quench factor values. These values can be related to the critical times using equation 2-4. Repeating equation 2-4 for various values of quench factors produces a set of nonlinear equations that can be solved using MATLAB to obtain the values of $C_t$.

# 3. EXPERIMENTAL PROCEDURE

## 3.1. JOMINY END QUENCH TEST

The JEQ apparatus is shown in Figure 3-1. The design of the system allowed adjustment of the height (0.5"-1") above the water orifice, the temperature of the water (5-30$^{o}$C), and the flow rate of water. The apparatus holder was covered with insulating tape to avoid conduction from the sample to the sample holder. The chemical composition of the wrought and cast (sand cast) aluminum alloys under study is shown in Table 3-1.

Table 3.1 Chemical composition of aluminum alloys used [3][8].

| Alloy | Si | Fe | Cu | Mn | Mg | Zn | Ti |
|---|---|---|---|---|---|---|---|
| 7075 | 0.1 | 0.2 | 1.36 | 0.04 | 2.62 | 5.77 | 0.017 |
| 6061 | 0.4-0.8 | 0.7 | 0.15-0.4 | 0.15 | 0.8-1.5 | 0.25 | 0.15 |
| A356 | 6.5-7.5 | 0.2 | 0.2 | 0.1 | 0.25-0.45 | 0.1 | 0.2 |
| B319 | 5.5-6.5 | 1.2 | 3.0-4.0 | 0.8 | 0.1-0.5 | 1 | 0.25 |

Prior to heating, specimens were cleaned with ethanol to remove dirt and other residual particles. The convection oven was heated to the solution treating temperature, and soaked for 2 hours to reduce the temperature recovery time once the specimens were placed in the furnace. Specimens were placed in the convection oven and held for times specified in Table 3-2. The temperatures and times shown in the table were selected based on the work of Mackenzie [3] and Mehta [8]. The solution treating temperatures were chosen to ensure a maximum amount of solute would go into the solid solution; the aging parameters were chosen to ensure that the alloy would be quench sensitive. The process included a delay of 1 hour or 120 hours aging so that the effect of such a delay on the final properties of the alloy could be observed. After the delay, the specimens were quickly removed from the oven and placed in the JEQ fixture, and the water flow valve was opened. The transfer time from the furnace to the fixture was less than 10 seconds. The umbrella of water flow stream seen in Figure 3-1 shows that the cooling was uniform and the sample was in line with the water valve.

The Jominy bar was cooled until the temperature of the specimens was less than 50$^{O}$C, typically 2-3 minutes, the specimen was removed from the test fixture and quenched in 25$^{O}$C water, this temperature was maintained by the addition of cold water as required.

Table 3.2 Test matrix for the alloys

| Alloy | 7075 | 6061 | A356 | B319 |
|---|---|---|---|---|
| Solution Treatment | 490$^{O}$C@12hr | 530$^{O}$C@12hr | 540$^{O}$C@12hr | 505$^{O}$C@12hr |
| Delay before Aging | 1 &120 hr | 1 &120 hr | 1 & 120 hr | 1 &120 hr |
| Aging Treatment | 120$^{O}$C@24hr | 175$^{O}$C@8 hr | 155$^{O}$C@3-5hr | 155$^{O}$C@2-5 hr |

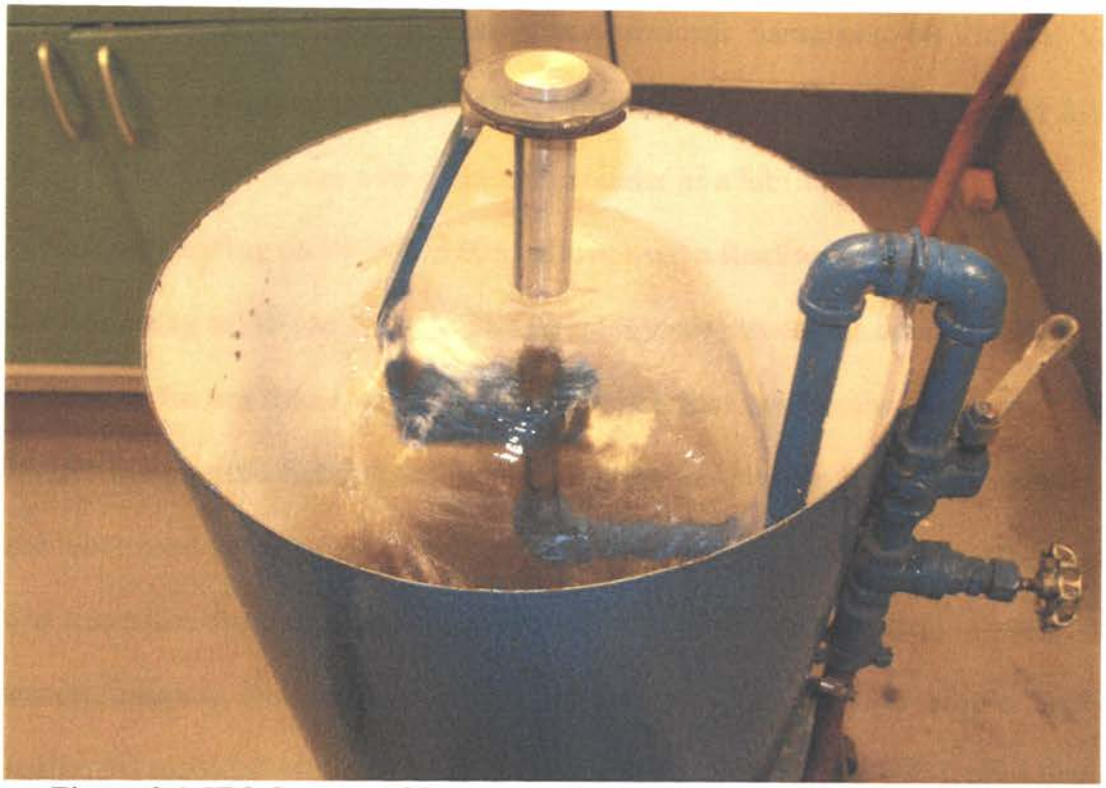


Figure 3.1 JEQ System with water umbrella indicating proper alignment.

### 3.2. AGING TREATMENT

The samples that were solutionized and JEQed were then aged. The delay before aging, aging temperature, and aging times are shown in Table 3-2. The furnace used for aging the specimens was also a convection oven. It was soaked at the appropriate temperature for 2 hours. After the specimens were aged, they were removed from the furnace and quenched in cold water at room temperature. Approximately 1.5mm was machined from each side of the specimen to allow grinding and polishing, and to facilitate hardness studies.

### 3.3. HARDNESS STUDIES

Hardness studies were peformed on heat treated and machined specimens. Samples were first hand ground using 240 grit SiC papers, followed by 320 grit, 400 grit, and 600 grit impregnated papers with water as a lubricant. Samples to be Vickers hardness tested were further polished using 3-micron diamond paste followed by 1 micron and 0.1 micron pastes with diamond extender as a lubricant.

Hardness testing on 7075 and 6061 alloys used a Rockwell hardness testing machine according to ASTM E18-07. The samples were placed in a special Jominy fixture fitted to the test frame, as in Figure 3-2. The initial hardness values were inconsistent because the fixture used did not hold the samples firmly, resulting in a moment when load was applied. The hardness values obtained were erratic, and some data was lost when the Avrami parameters were calculated. Another sample was placed in a second fixture as shown in Figure 3-3. The second fixture held the sample firmly, eliminating the moment when the load was applied. The first fixture had screws that held the sample at the top and bottom of the bar, accounting for the moment when load was applied. The second fixture had small flat plates that held the sample at the top and bottom.

As explained in section 2.6, hardness at a point along the Jominy bar can be calculated using equation 2-4. Rearranging the equation and taking the natural logarithm twice on both sides, the hardness values can be plotted as a function of distance from quenched end. The straight line obtained gives the values of the Avrami exponent n, and the intercept of the equation gives the value of the Avrami constant k. Typical hardness values obtained from the first fixture are shown in Figure 3-4; those obtained from the second fixture are shown in Figure 3-5. A comparison of these figures shows that the hardness values obtained from the second fixture gave a better fit than those from the first fixture.

Hardness testing on cast alloys A356 and B319 was peformed using a Vickers hardness testing machine according to ASTM E92-82. Vickers hardness testing with a 1 kg load produces the best results for hardness measurements of A356 and B319 aluminum alloys [8]. Since Vickers hardness measurements permitted collection of more data, more precise measurements and more accurate results were obtained [36]. In case of a discrepancy in the reading, Vickers hardness testing also permits rechecking by measuring the diagonals or by placing an additional indent alongside the disputed reading. There was no special fixture for Vickers. The load was less (1 kg) than that used in the Rockwell hardness testing (100 kg), and no moment was observed when the load was applied.

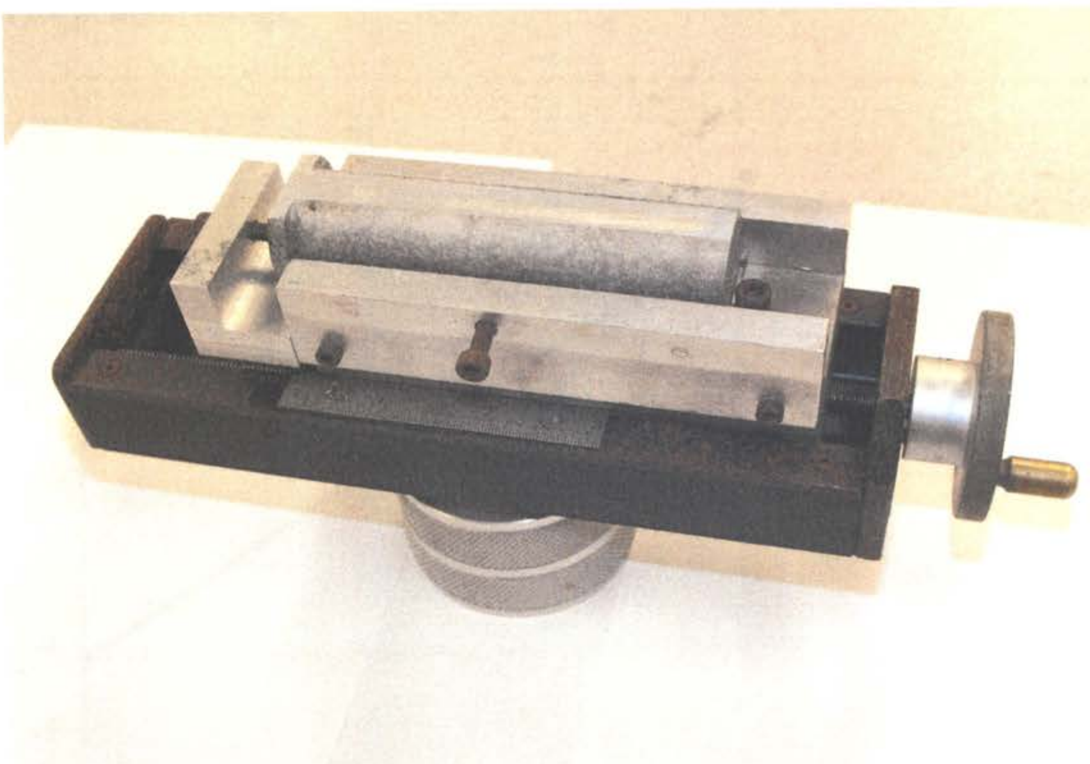


Figure 3.2 First fixture used for hardness testing, with Jominy sample and indexing wheel for position change

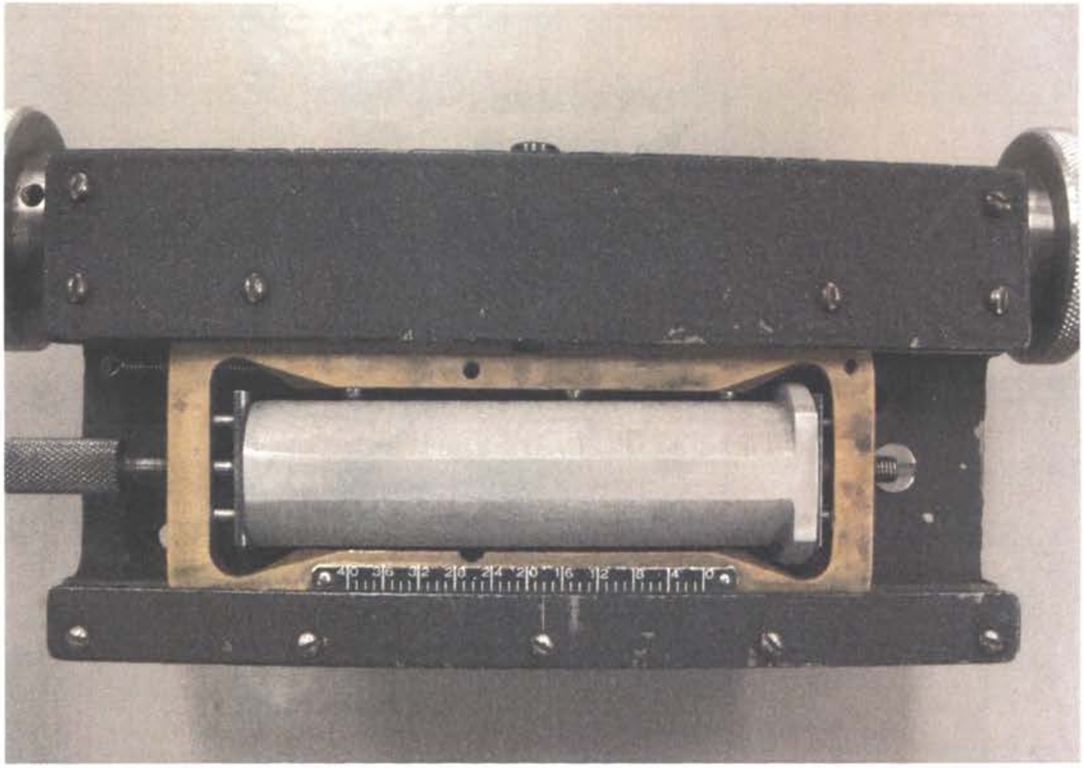


Figure 3.3 Second fixture used for hardness testing, with Jominy sample and indexing wheel for position change.

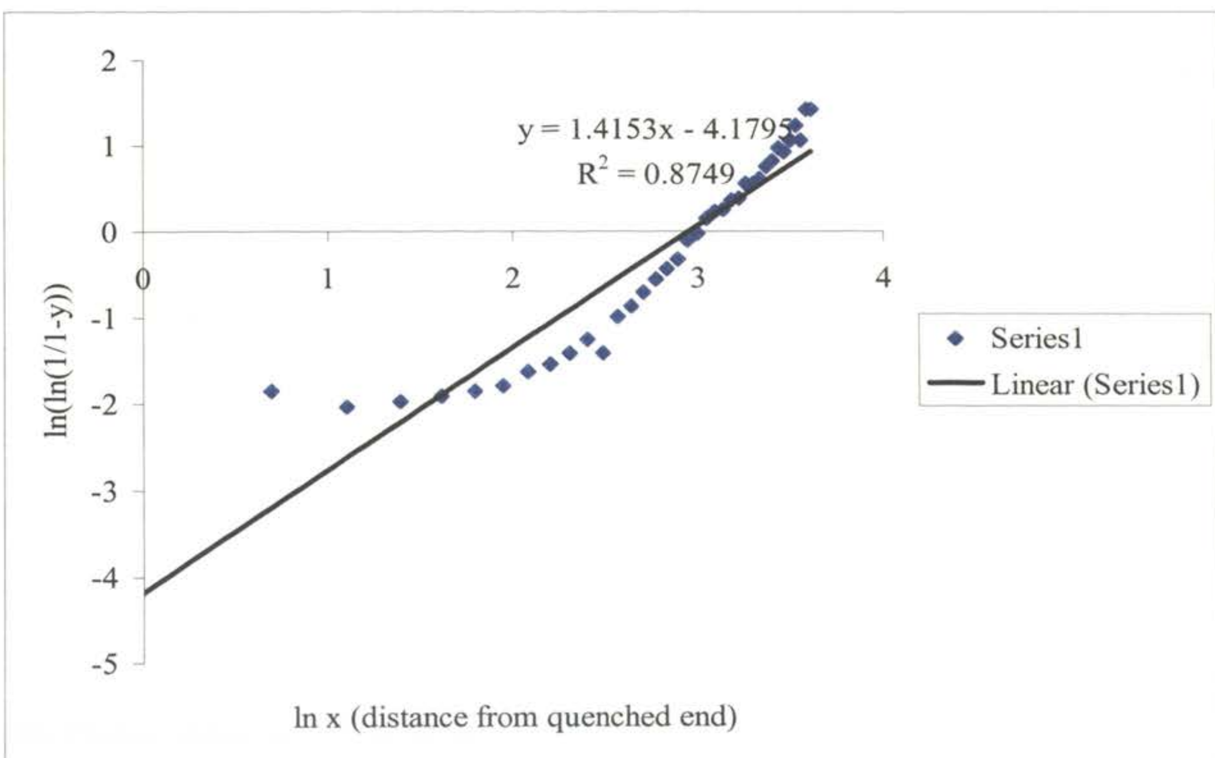



Figure 3.4 Hardness as a function of distance from the quenched end with the first fixture.

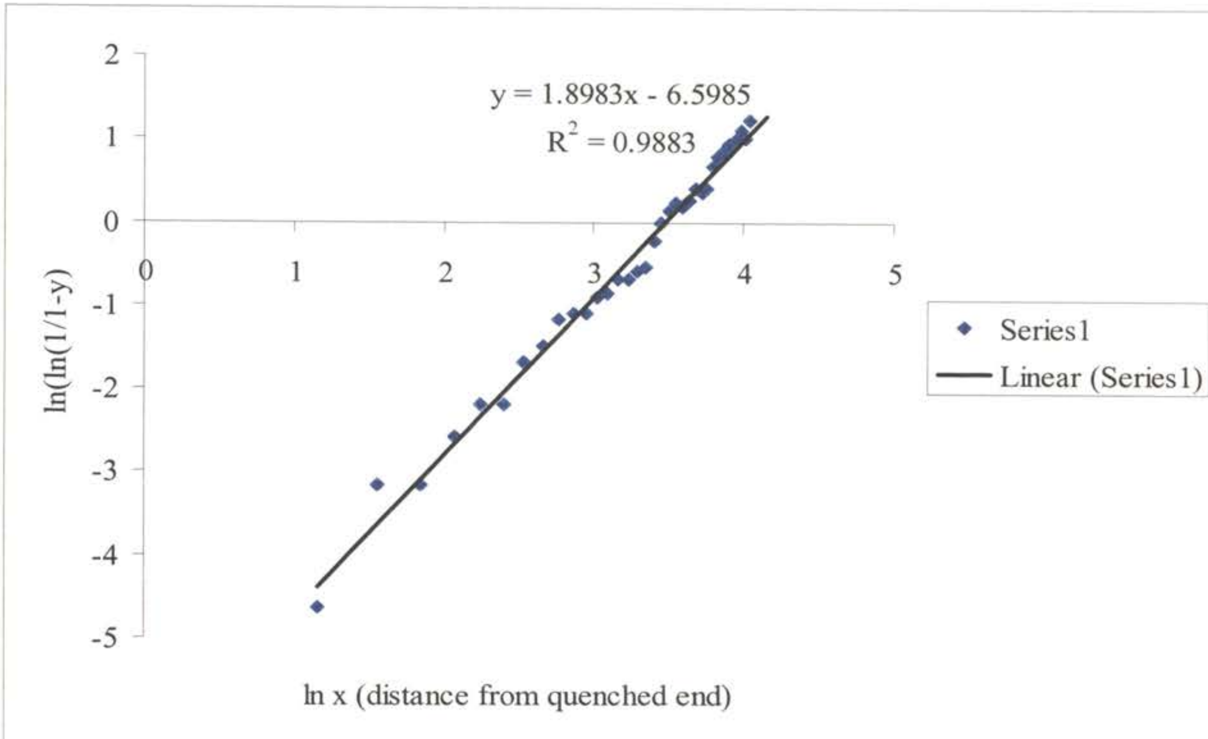



Figure 3.5 Hardness as a function of distance from the quenched end with the second fixture.

### 3.4. MINI TENSILE TESTING

Using an abrasive saw, 1.5mm thick slices were cut from various locations along the Jominy bar for mini tensile testing. The locations were selected using the experimental hardness curves so that one point lay on each plateau and the remaining two points lay in the transition range. On each slice, four mini tensile test samples were machined using a computer numerical control (CNC) mini mill to obtain different types of mini tensile samples. A schematic of the sample used for testing is shown in Figure 3-6. The positioning of mini tensile specimens on the slice is shown in Figure 3-7.

The slices were cleaned with ethanol, then glued onto a flat piece of metal using 3M "Instant Krazy glue." Samples were milled using the CNC mill, and then submerged in ethanol overnight to dissolve the glue. The slices were then ground on the unmilled side until the edges of the samples were clearly visible. The samples were then hand ground on each side starting with SiC 240 grit, followed by 320 grit, 400 grit, and 600 grit with water as a lubricant. They were polished with 3-micron diamond paste, followed by 1 micron, and finished with 0.1 micron. Diamond extender was used as a lubricant for polishing.

The polished samples were tested using the mini tensile test frame. This test frame consisted of a 100-lb load cell and a linear variable differential transformer (LVDT) to measure the displacement, as shown in Figure 3-8. The test frame was connected to a computer, and the loading program was written using Lab View software. The strain rate used for the testing was $10^{-3}\ s^{-1}$. Before testing, the sample was preloaded to approximately 3 lbs to prevent slip in the grips. Once the test began, a load was applied based on the sample dimensions, such as gage length, thickness, and width. The output data included the load versus time values. These data were converted into stress and strain values:

$$\text{Stress} = P/(w*t) \qquad 3\text{-}1$$

where P is the load at a given time, w is the width of the sample, and t is the thickness of the sample. Similarly, strain is determined by

$$\text{Strain} = \text{Strain rate} * \text{Time} \qquad 3\text{-}2$$

The stress-strain curves were plotted using these data, and the ultimate tensile strength was obtained from these plots. The yield stress was obtained by drawing a line parallel to the elastic region of the stress-strain curve from 0.2% of strain.

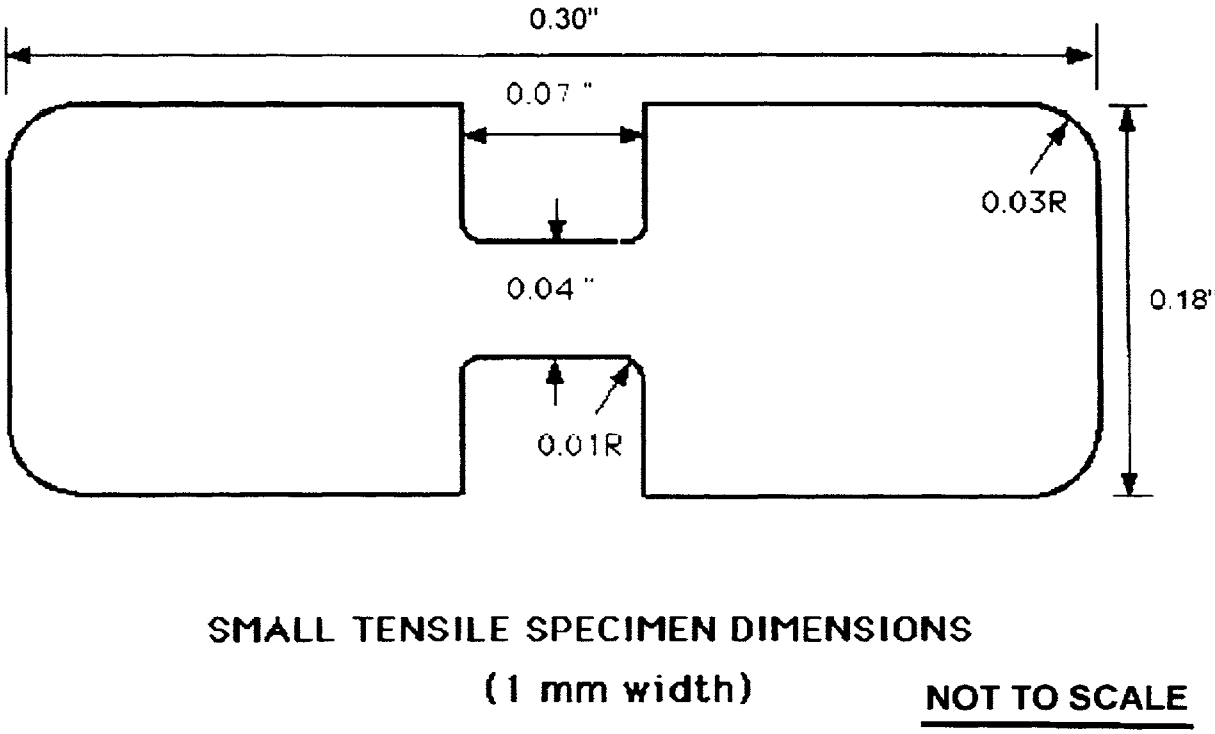



Figure 3.6 Mini tensile test sample used for tensile testing.

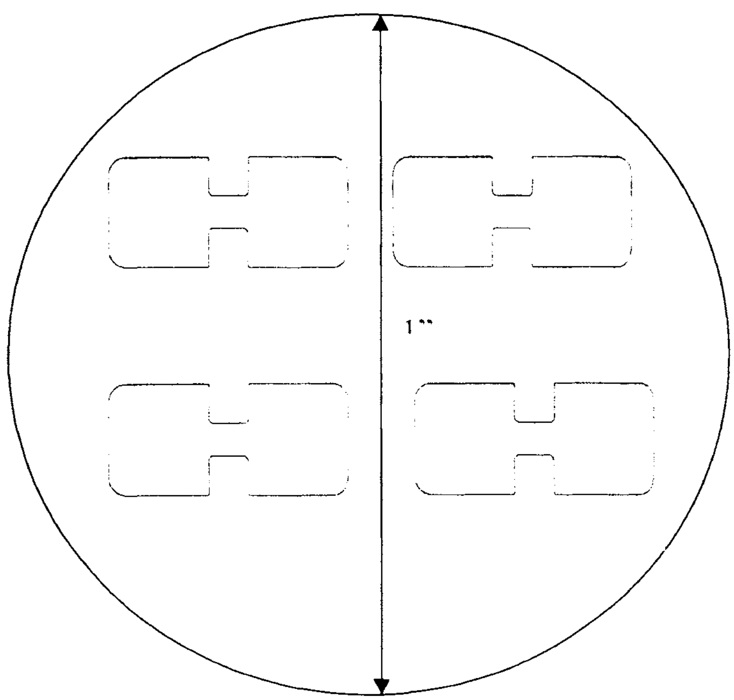



Figure 3.7 Positioning of the mini tensile specimens on the slice from JEQ cylinder.

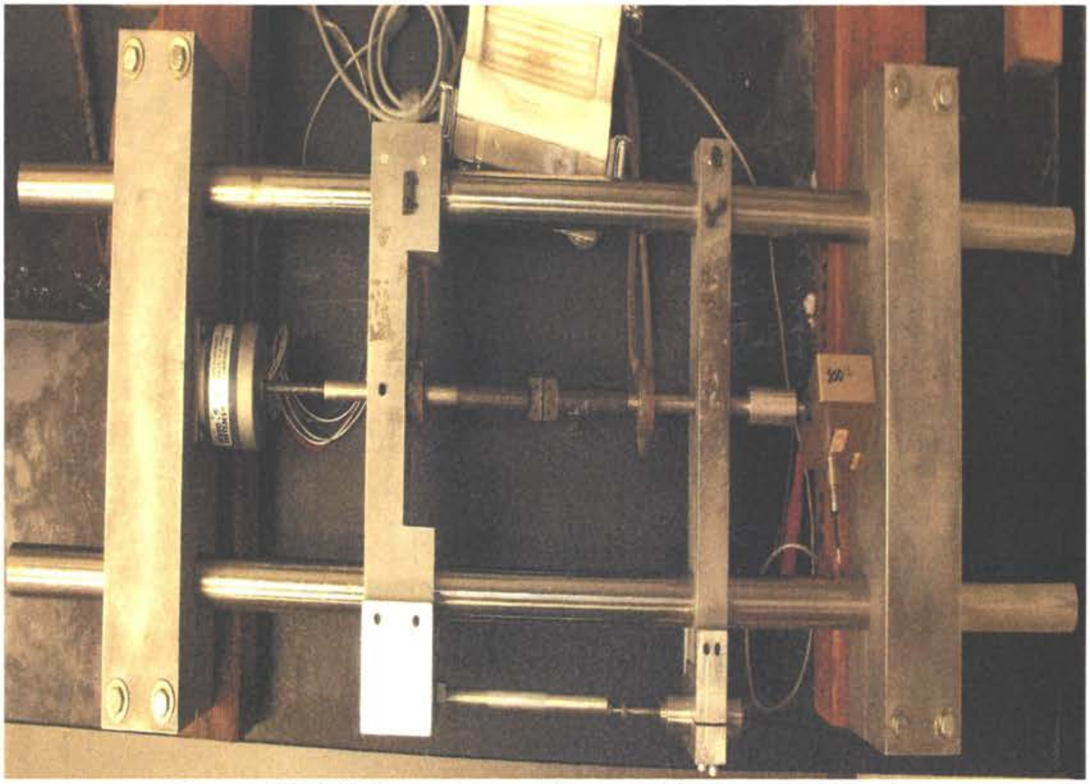


Figure 3.8 Mini tensile test frame with the cross heads.

### 3.5. SIMULATION OF COOLING CURVES

For the quench factor analysis, the temperature increments are needed to determine the values of $C_t$. The cooling curves were simulated using FLUENT 6.3.26 software, and the model was created using GAMBIT. A solid cylinder 4" high and 1" in diameter replicating a Jominy bar was used to develop this model. The solid geometry created was then meshed using a hexagonal/wedge element. After meshing, the model was exported to FLUENT as a case file, opened, and checked for errors. Once free of errors, operating and boundary conditions were applied to simulate the cooling process. The boundary conditions chosen in this case were those for convective heat transfer. The convective heat transfer coefficient for wrought and cast alloys was selected based on previous studies [3, 8]. Images of the meshed sample are shown in figures 3-9 through 3-11.

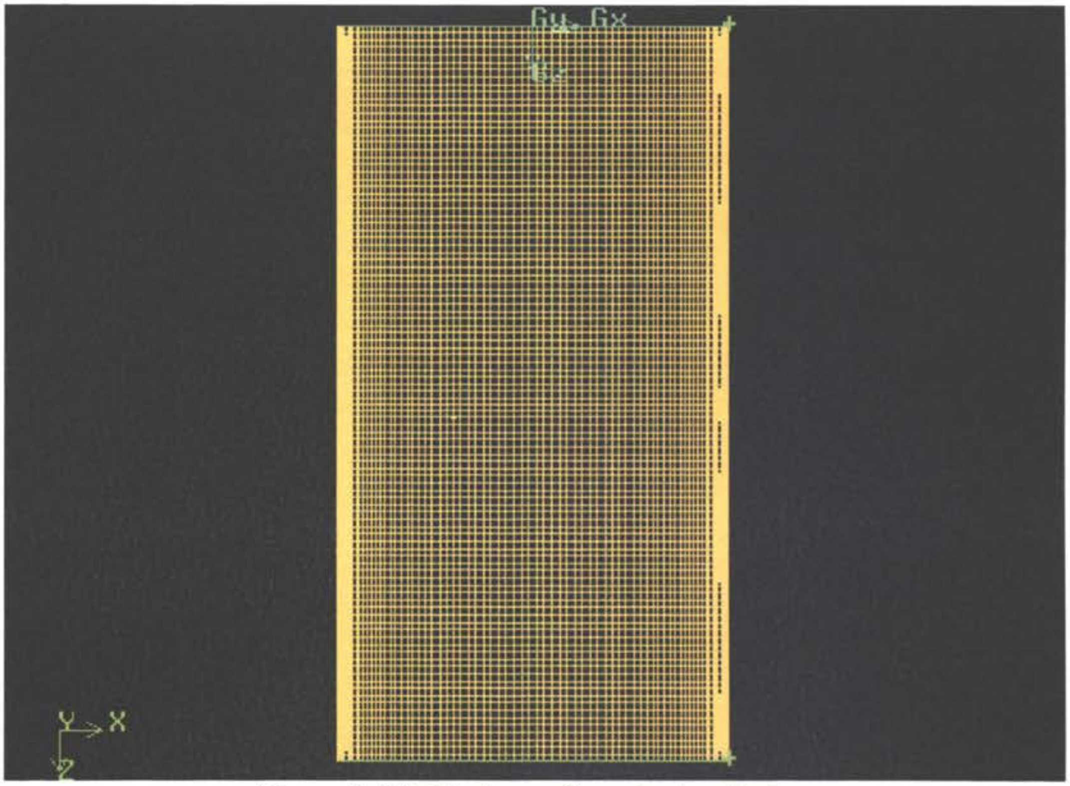


Figure 3.9 2-D view of meshed cylinder.

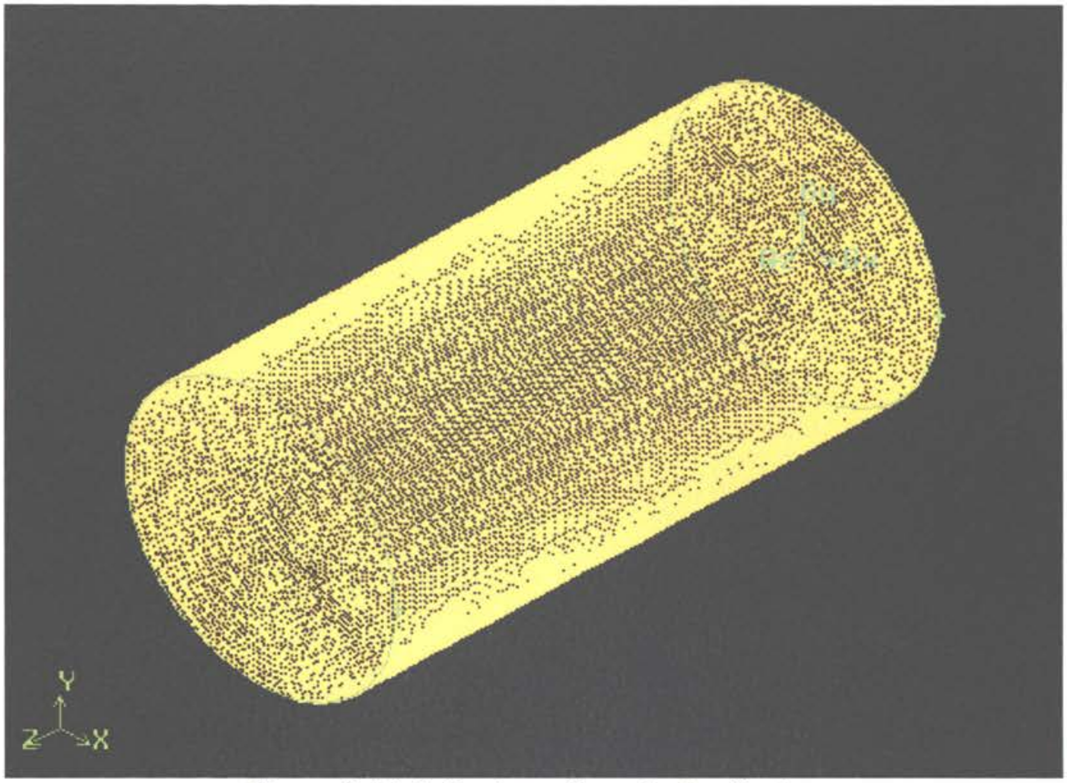



Figure 3.10 3-D view of meshed cylinder.

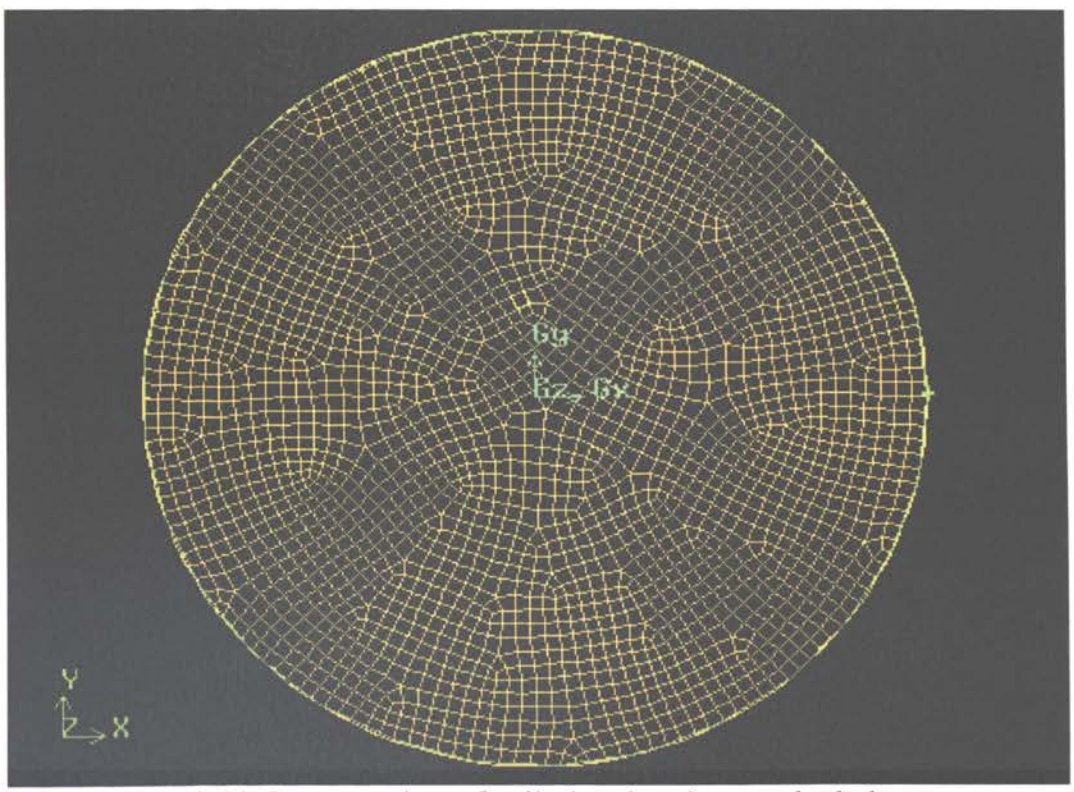



Figure 3.11 Cross section of cylinder showing meshed elements.

The simulated temperature versus time curves were plotted for the Jominy sample at various points. Figure 3.12 shows the cooling curves at eight different locations on the Jominy bar. The values obtained from the simulation were compared to the thermocouple data and found to be a good match. The comparison between the thermocouple and simulated curves is shown in Figure 3.13.

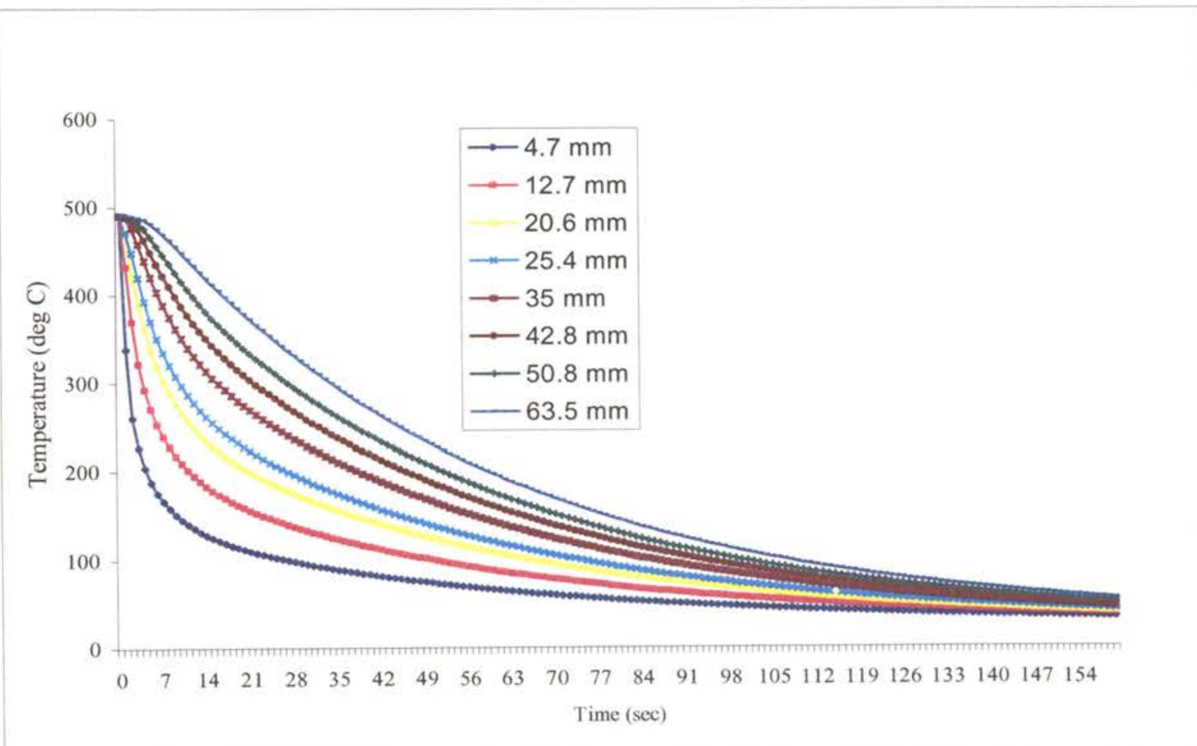



Figure 3.12 Simulated cooling curves at various locations on the Jominy Bar for 7075.

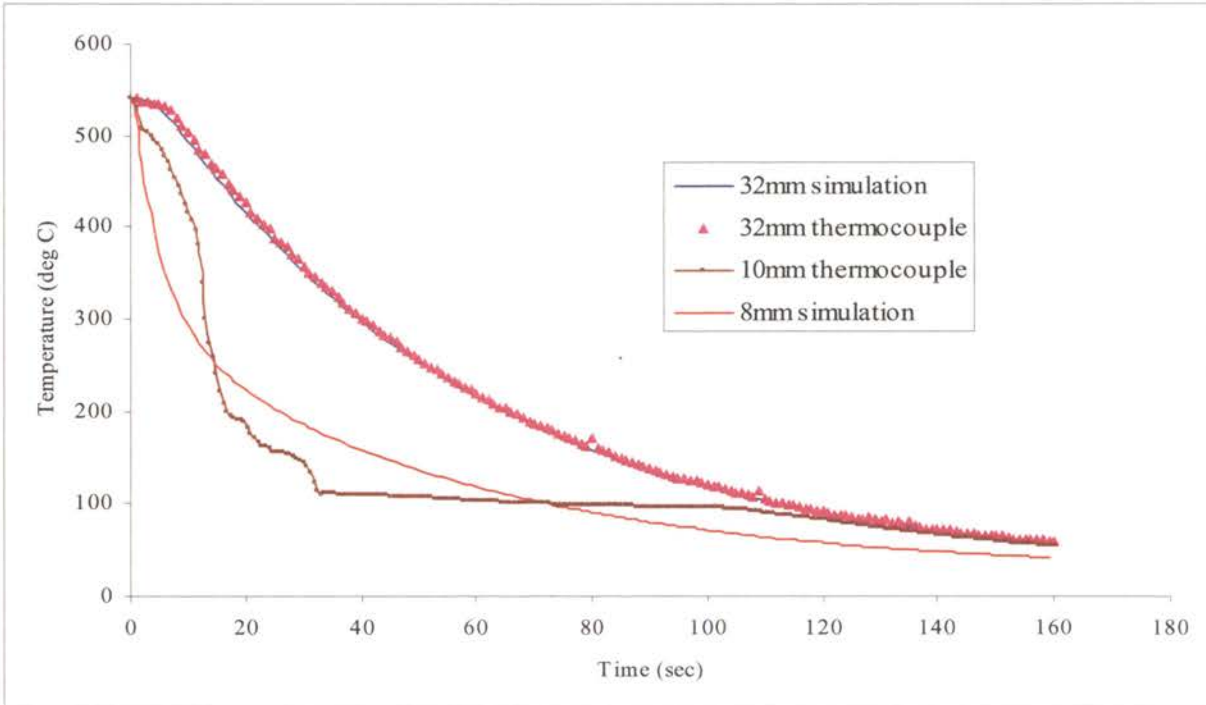



Figure 3.13 Comparison between simulated and thermocouple cooling curves.

For the quench factor analysis, the incremental times were calculated from the cooling curves.

# 4. RESULTS AND DISCUSSION

## 4.1. HARDNESS VERSUS JOMINY DISTANCE PLOTS

Four Jominy bars of 7075, 6061, A356, and B319 (with two-in-one heat treatment condition) were solution heat-treated, quenched, and aged according to the test conditions summarized in Table 3-1. These conditions were selected based on previous studies by Mackenzie [3] and Mehta [8]. The solution treatment temperature was selected such that all elements went into solid solution. The delay before aging was used to determine its effect on the properties. Prior studies show that increasing the delay before aging increases the hardness [3]. The aging time and temperature used were for T6 temper of each of these four alloys. Mackenzie [3] studied the effect on 7075. The present study analyzed the effect of those parameters on other alloys. In Figures 4-1 through 4-8, the experimental hardness values are shown as points, and the Avrami fit curves are shown as lines. The Avrami fit was done using the experimental values and equation 2-4.

$$H(x) = H_{max} - \Delta H(1 - \exp(-kx)^{n}) \qquad (4\text{-}1)$$

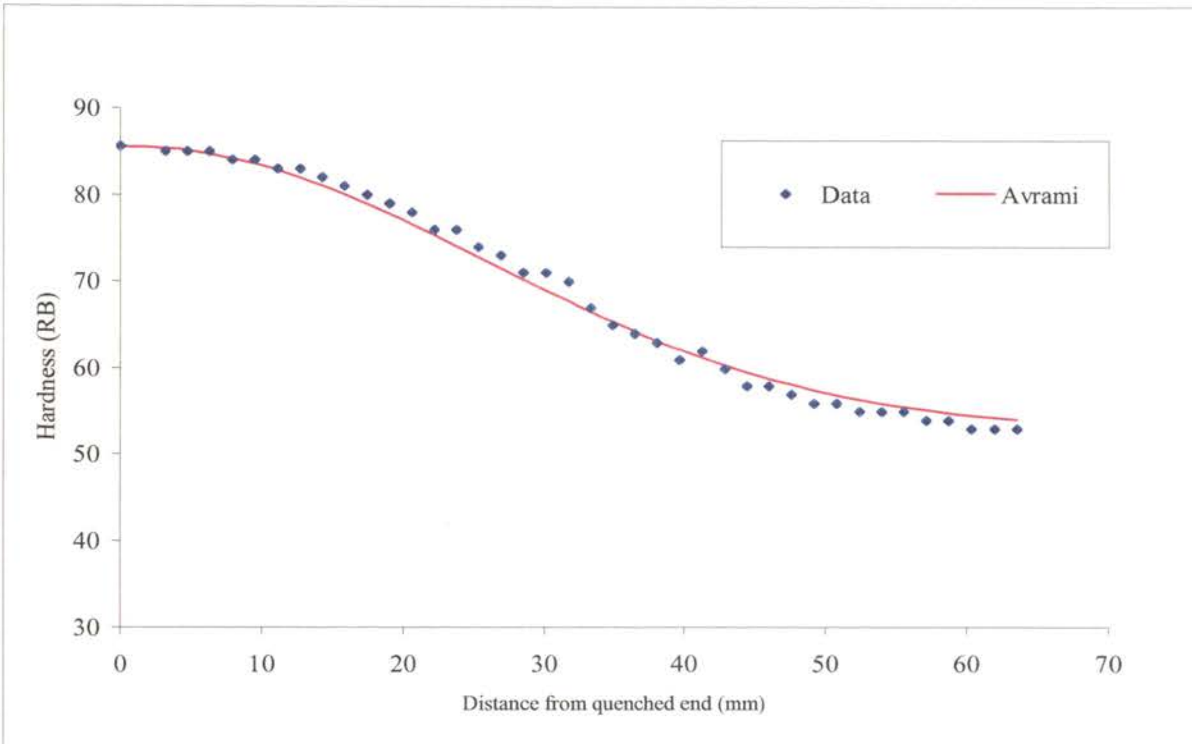



Figure 4.1. Rockwell B Hardness plots for Avrami and experimental values of 7075, with 1-hr delay.

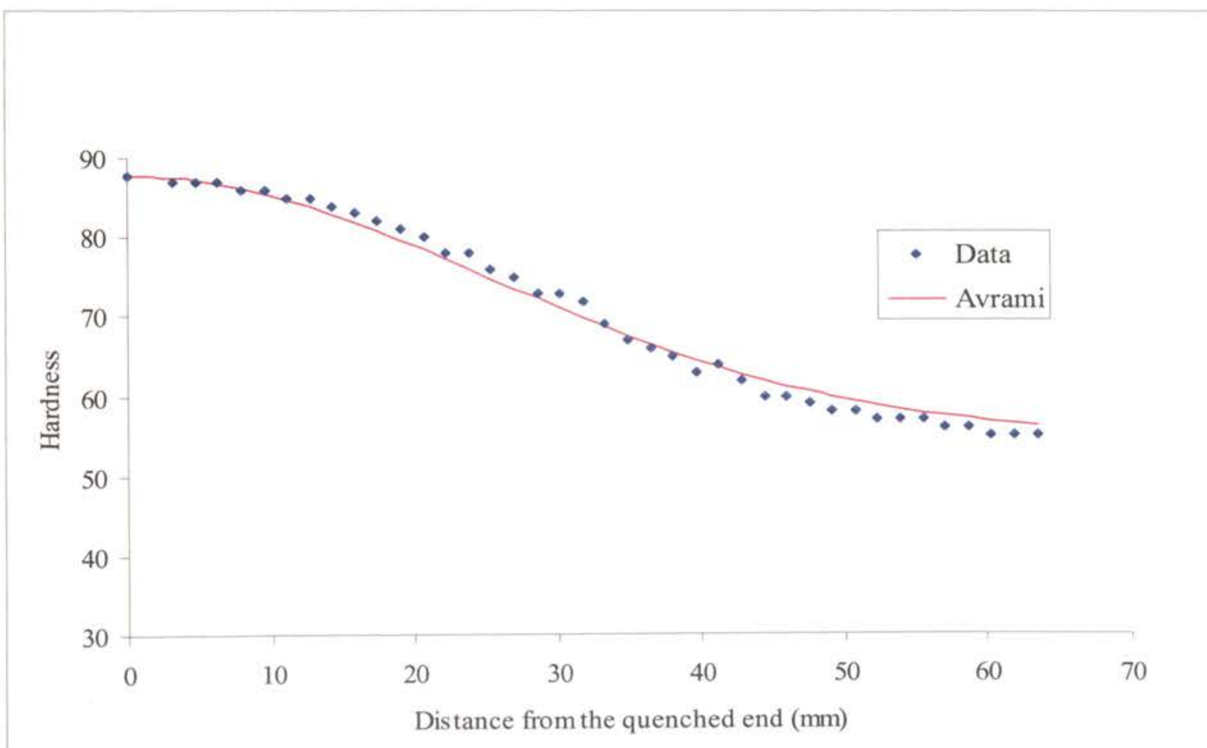



Figure 4.2. Rockwell B Hardness plots for Avrami and experimental values of 7075, with 120-hr delay.

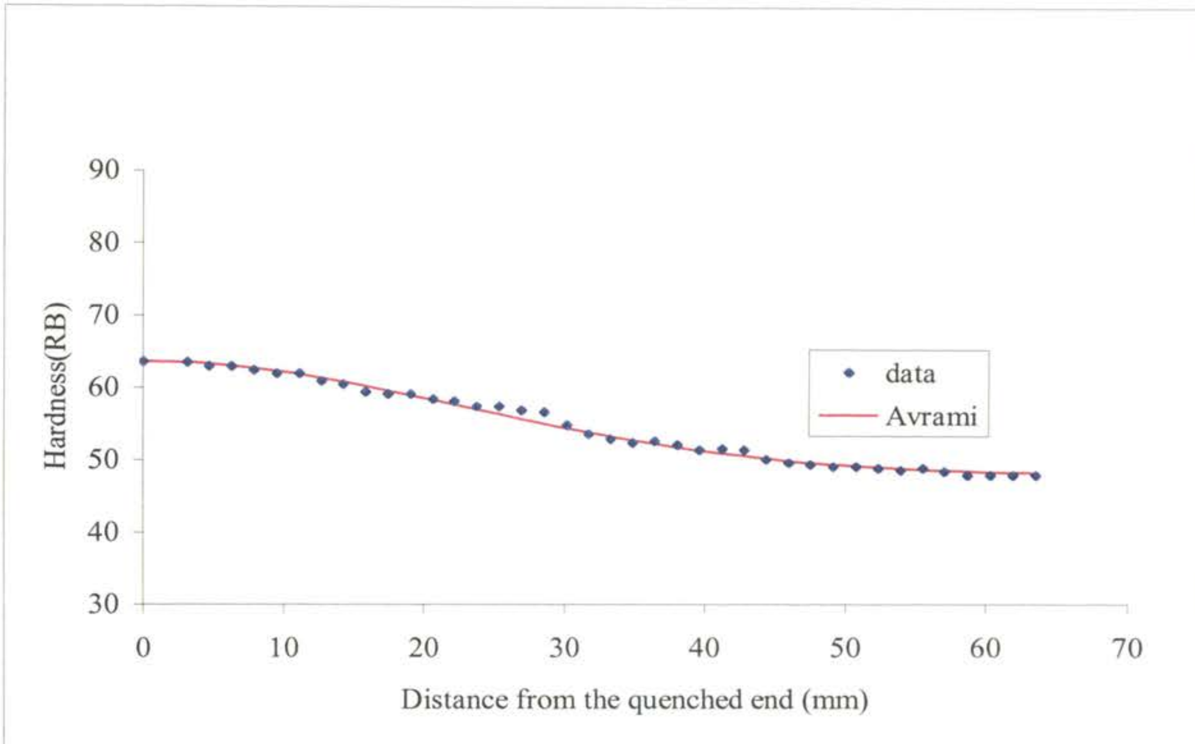



Figure 4.3. Rockwell B Hardness plots for Avrami and experimental values of 6061, with 1-hr delay.

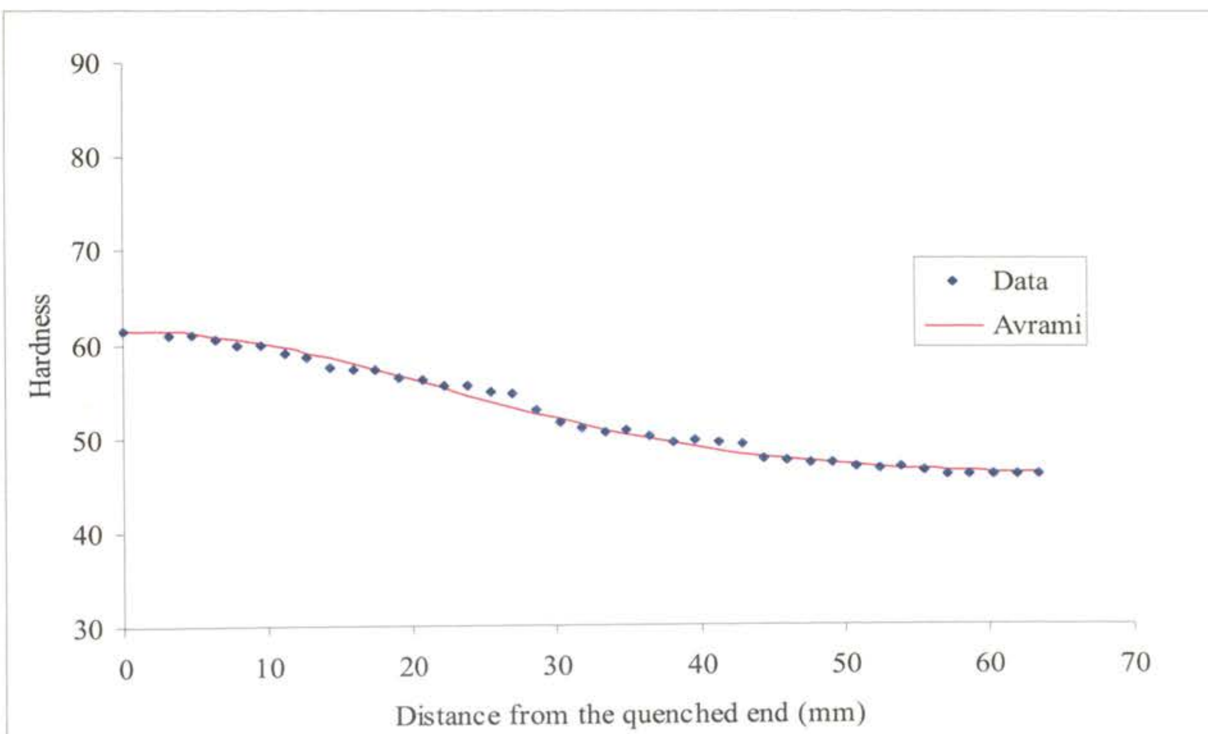



Figure 4.4. Rockwell B Hardness plots for Avrami and experimental values of 6061, with 120-hr delay.

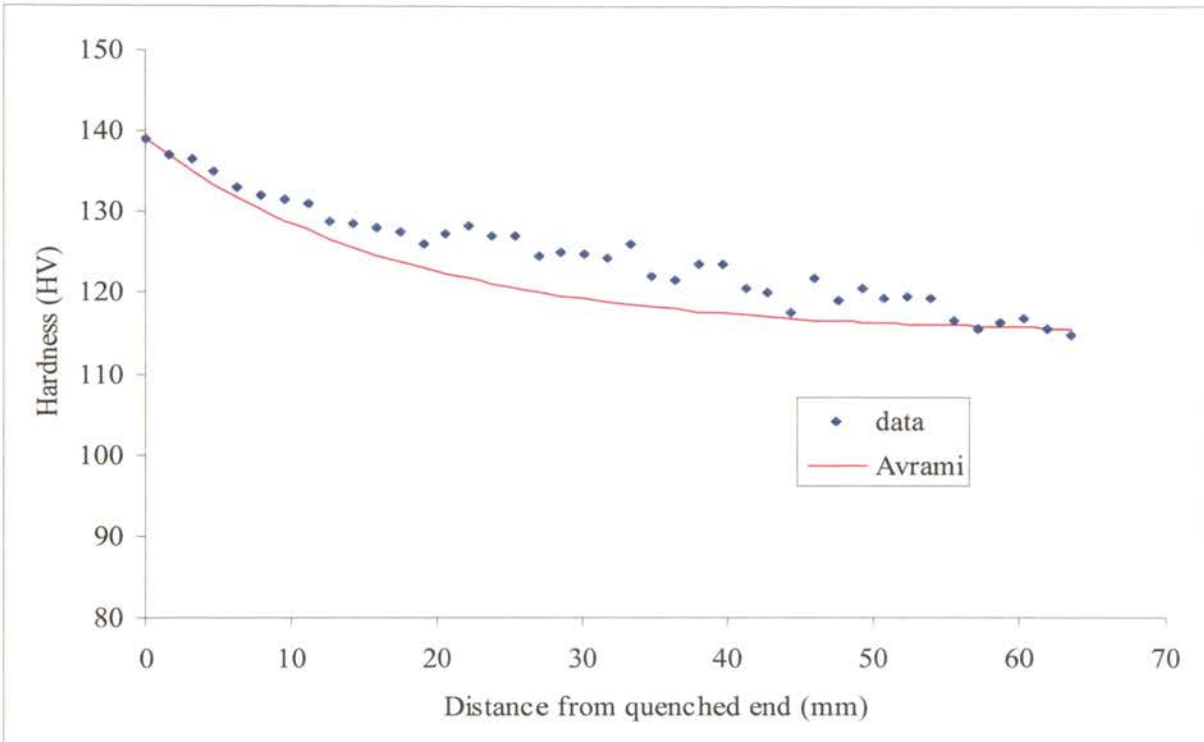



Figure 4.5. Vickers microhardness plots for Avrami and experimental values of B319, with 1-hr delay.

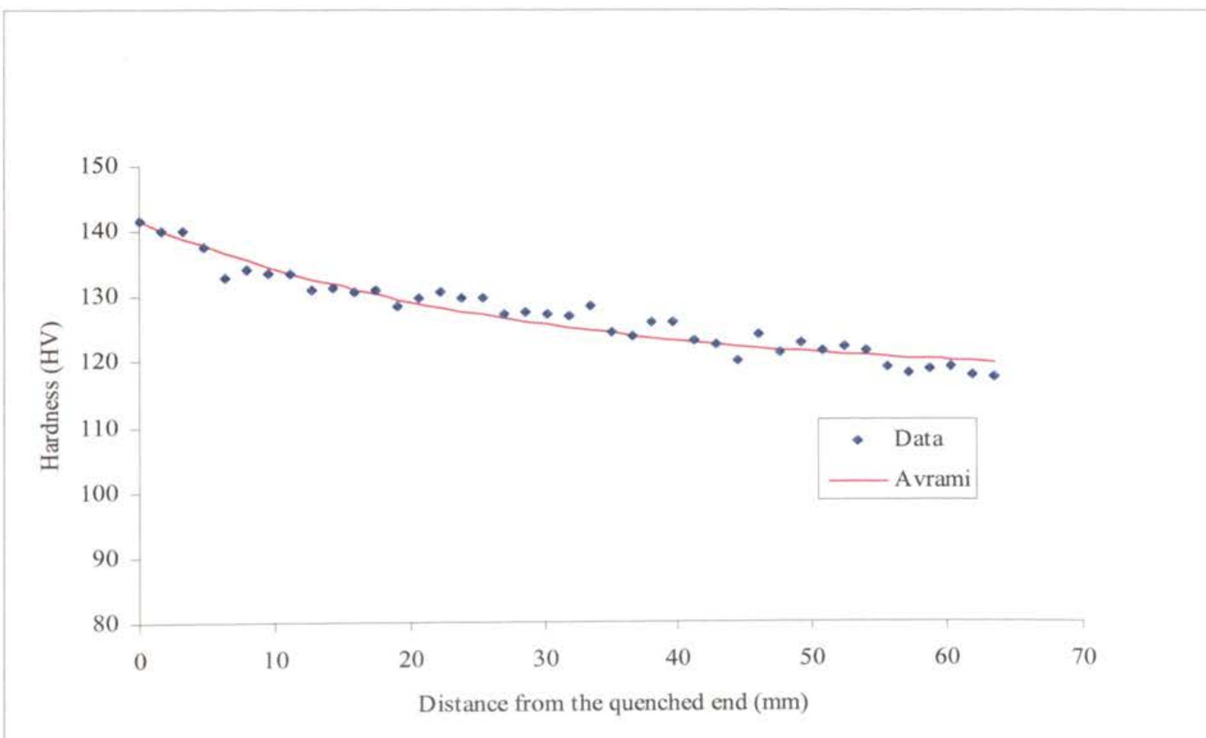



Figure 4.6. Vickers microhardness plots for Avrami and experimental values of B319, with 120-hr delay.

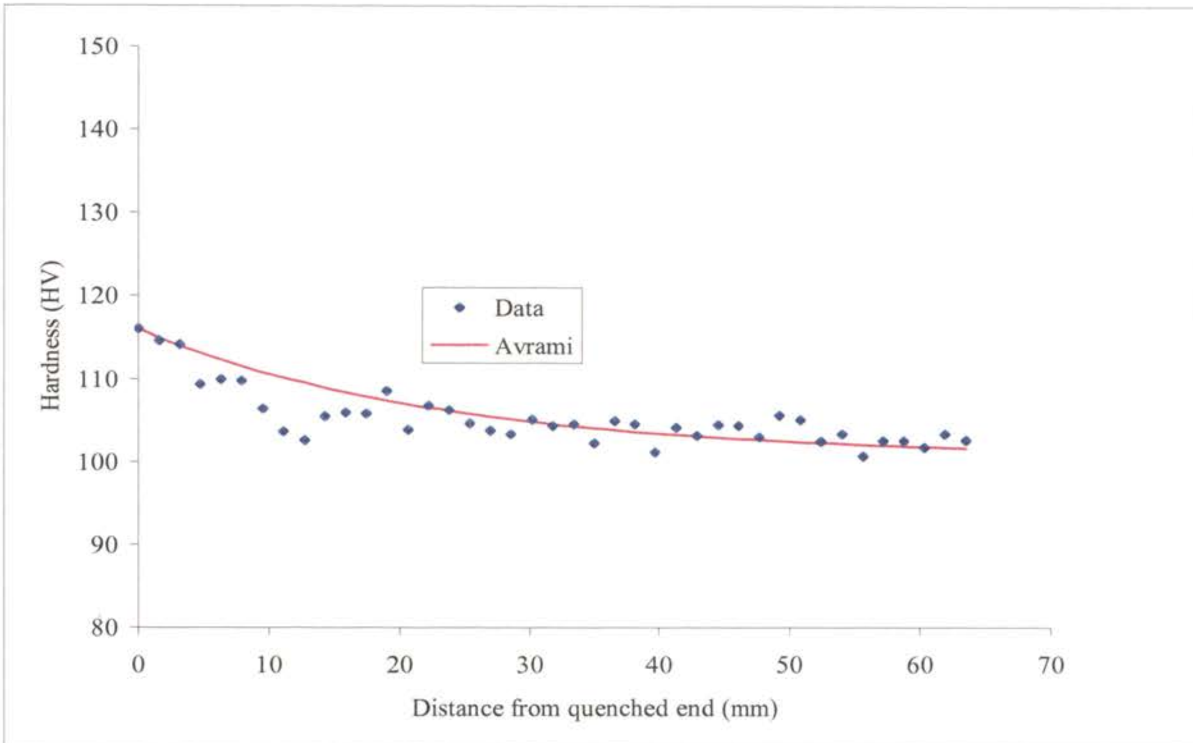



Figure 4.7. Vickers microhardness plots for Avrami and experimental values of A356, with 1-hr delay.

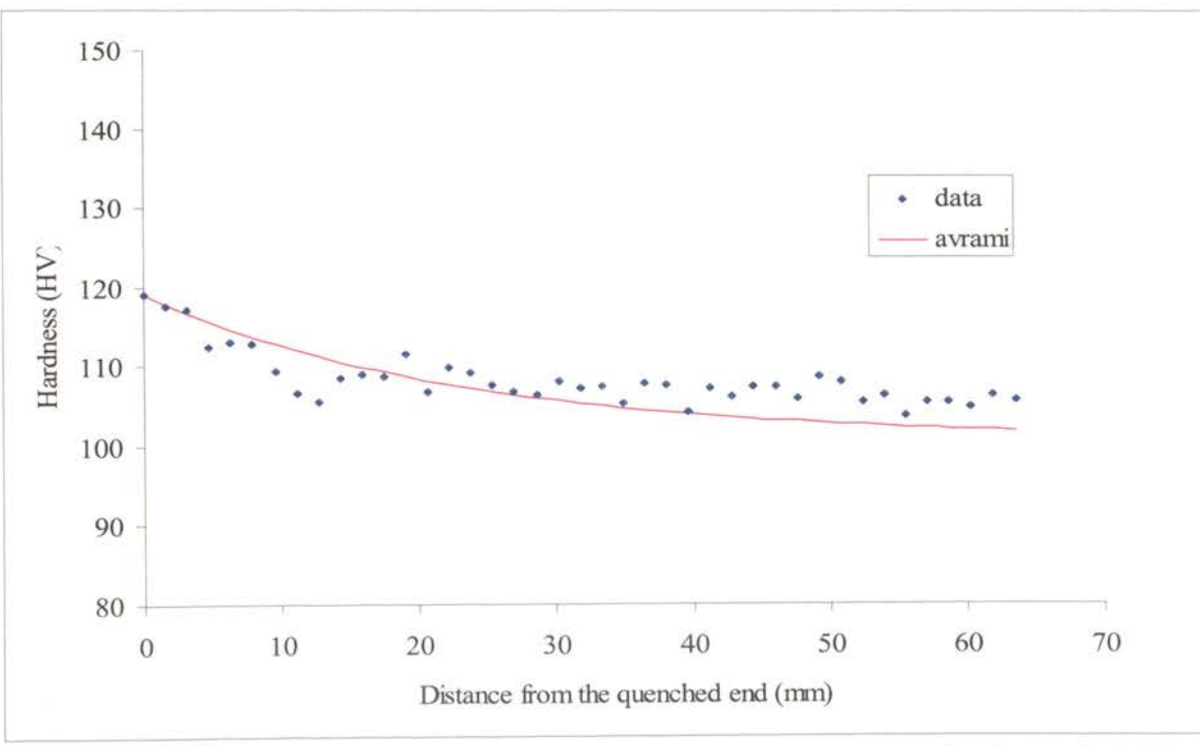



Figure 4.8. Vickers microhardness plots for Avrami and experimental values of A356, with 120-hr delay.

Figures 4.1. and 4.2. show the hardness plots for samples of 7075 with a 1-hr delay and a 120-hr delay respectively. As noted above, the hardness curves follow an Avrami relationship. The curves show that hardness values obtained using the Avrami fit are a good match with the experimental values. For the sample with a longer delay time before aging, $H_{max}$ was higher than for the sample with a shorter delay. The other figures show that hardness values were higher for samples with longer delay times before aging which agrees with previous studies [3] [9]. The difference between the maximum and minimum hardness $\Delta H$ for wrought alloys and $H_{max}$ for both the heat treatments is shown in Table 4.1; that for cast alloys is shown in Table 4.2. The difference between the maximum and minimum hardness is $\Delta H$, which describes the quench sensitivity of the alloys. Table 4.1. shows that 7075 is more quench sensitive than 6061 as expected.

In the case of cast alloys, the specimen with a longer delay before aging had higher hardness. Also, B319 proved more quench sensitive than A356. The quench sensitivity of 7075 is the same as that reported by Mackenzie [3]. At peak hardness, however, $H_{max}$ values for the cast alloys do not agree with work done by Mohammadi [9], perhaps due to differences in the heat treatment parameters. Mohammadi [9] used delays of 10 min and 1 week to optimize the heat treatment parameter for cast aluminum alloys.

The values of Avrami exponent n and Avrami constant k for wrought alloys 7075 and 6061 are shown in Table 4.3. and those for cast alloys A356 and B319 are shown in Table 4.4.

Table 4.1. Maximum hardness and hardness difference values for 7075 and 6061

| Alloy | 7075 1hr delay | 7075 120hr delay | 6061 1hr delay | 6061 120hr delay |
|---|---|---|---|---|
| ΔH | 32±2 $R_B$ | 30±2 $R_B$ | 16±1 $R_B$ | 15±1 $R_B$ |
| $H_{max}$ | 85±0.6$R_B$ | 88±0.7$R_B$ | 61.5±0.5$R_B$ | 64±.05$R_B$ |

Table 4.2. Maximum hardness and hardness difference values for A356 and B319

| Alloy | A356 1hr delay | A356 120hr delay | B319 1hr delay | B319 120hr delay |
|---|---|---|---|---|
| ΔH | 18±2 HV | 17±1 HV | 24±2 HV | 22±2 HV |
| $H_{max}$ | 116 HV | 119 HV | 139 HV | 141.5 HV |

Table 4.3. Values of Avrami parameters k and n for 7075 and 6061 wrought alloys with different heat treatments

| Alloy | 7075 1hr delay | 7075 120hr delay | 6061 1hr delay | 6061 120hr delay |
|---|---|---|---|---|
| k | 0.028 | 0.028 | 0.032 | 0.032 |
| n | 2.09 | 1.98 | 1.9 | 1.73 |

Table 4.4. Values of Avrami parameters k and n for A356 and B319 cast alloys with different heat treatments

| Alloy | A356 1hr delay | A356 120hr delay | B319 1hr delay | B319 120hr delay |
|---|---|---|---|---|
| k | 0.075 | 0.075 | 0.057 | 0.057 |
| n | 0.92 | 0.92 | 0.96 | 0.96 |

The tables 4-3 and 4-4 indicate that the values of Avrami constant k and Avrami exponent n are the same for a given set of alloys irrespective of the heat treatment cycle. The values of k and n for wrought alloys do not match previous work; however, the fit with experimental data (>95% match) is excellent. The discrepancy between the values reported here and those obtained by previous studies may be due to differences in the technique used to establish the parameters. Mackenzie [3] and Mohammadi [8] used the trend curves to fit the hardness values with Avrami parameters. Here, however, the Avrami parameters are mathematically calculated using the hardness values. In the case of A356, the value of n was in agreement with studies done by Sisson et al. [42]. As discussed above, the Avrami exponent n depends on the precipitation mechanism and geometry of growth, and the value of Avrami constant k is a complex factor of nucleation time and quench rate. The same values of k and n for the alloy show that the precipitation mechanism and the critical time for nucleation and growth of precipitates is the same for a particular alloy, irrespective of the delay before aging.

The hardness graphs in Figures 4.1. through 4.8. show the experimental data points and the Avrami fit for the data points. The Avrami fit curve generated does not perfectly match the experimental values in the case of minimum hardness. The calculated deviation of the fit from the experimental values is shown in Table 4.5. and Table 4.6. The error values show that in each case the error is less than 5%.

Table 4.5. Deviation of Avrami fit values of hardness from experimental values for wrought alloys

| Alloy | $H_{min}$ | $H_{min}$ (fit) | $H_{min}$(fit)-$H_{min}$ | Error (%) |
|---|---|---|---|---|
| 7075 1 hr delay | 53 | 54.14 | 1.14 | 2.15 |
| 7075 120 hr delay | 55 | 56.42 | 1.42 | 2.58 |
| 6061 1 hr delay | 48 | 48.33 | 0.33 | 0.69 |
| 6061 120 hr delay | 46 | 46.23 | 0.23 | 0.50 |

Table 4.6. Deviation of Avrami fit values of hardness from experimental values for cast alloys

| Alloy | $H_{min}$ | $H_{min}$ (fit) | $H_{min}$(fit)-$H_{min}$ | Error (%) |
|---|---|---|---|---|
| A356 1 hr delay | 102.7 | 101.76 | -0.94 | -0.92 |
| A356 120 hr delay | 105.7 | 101.95 | -3.75 | -3.55 |
| B319 1 hr delay | 117.5 | 119.95 | 2.45 | 2.09 |
| B319 120 hr delay | 115 | 115.64 | 0.64 | 0.56 |

## 4.2. MINI TENSILE TESTING

Wei [30] studied the quench effect on properties of Al-Zn-Mg-Cu alloys using tensile specimens from Jominy plate end quench samples. Mini tensile tests have been done on JEQ samples to study their tensile properties and the effect on those properties of delay. The main advantage of using the mini tensile testing rather than normal tensile testing is smaller sample size and repeatability. Here, mini tensile specimens were obtained from various locations on the Jominy bar. Based on the results of hardness testing, four points were selected, from which the entire Avrami curve can be regenerated. A point was taken from each plateau, and two points were taken from the transition region. Figures 4.9 through 4.16 show the UTS and YS for 7075 and 6061 alloys. Mini tensile testing produces tensile properties with statistically significant values through JEQ testing of a single specimen. The experimental values $\sigma_{max}$ and $\sigma_{min}$ can be then calculated, and $\Delta\sigma$ can be evaluated. These values are used to regenerate the Avrami curve.

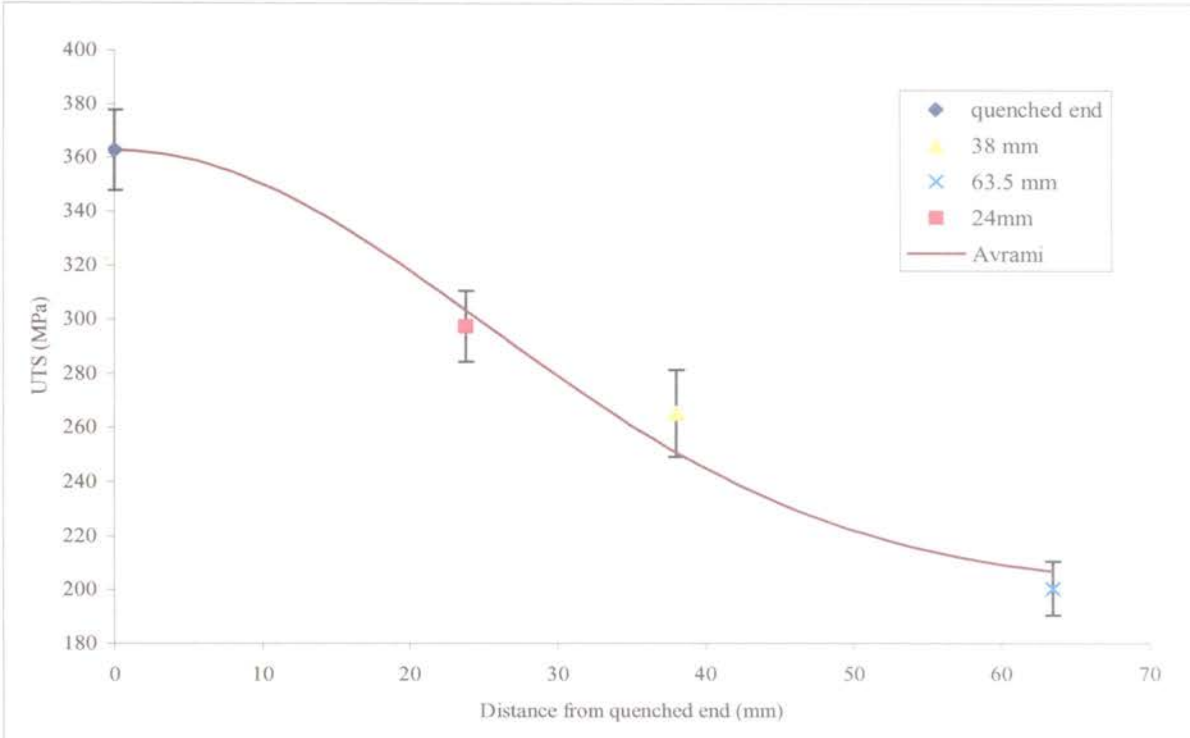



Figure 4.9. Variation of UTS with Jominy distance for 7075 with 1-hr delay

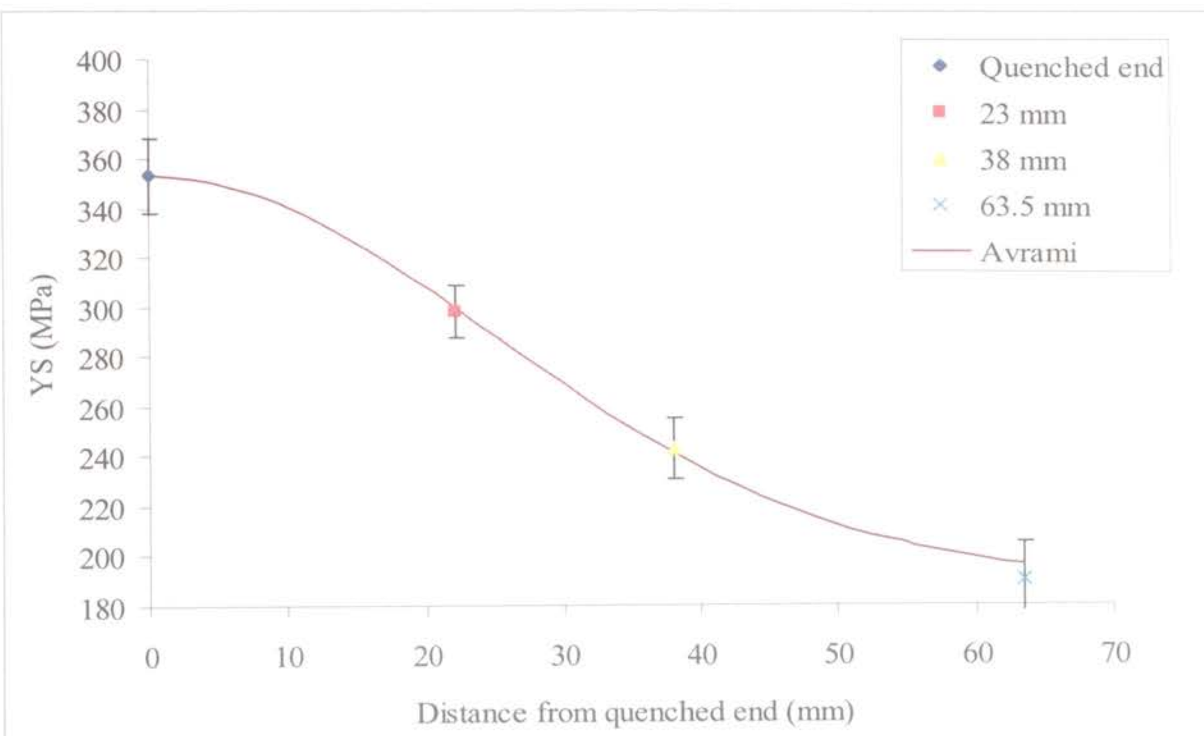



Figure 4.10. Variation of YS with Jominy Distance for 7075 with 1-hr delay

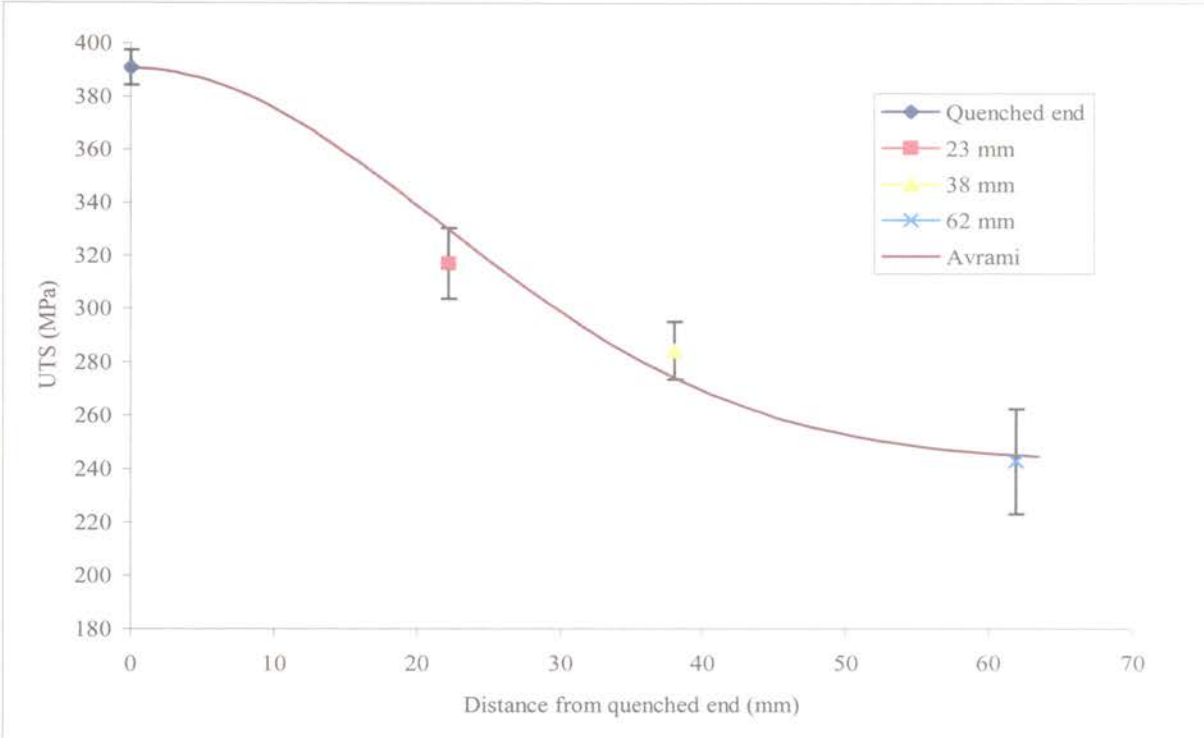



Figure 4.11. Variation of UTS with Jominy distance for 7075 with 120-hr delay

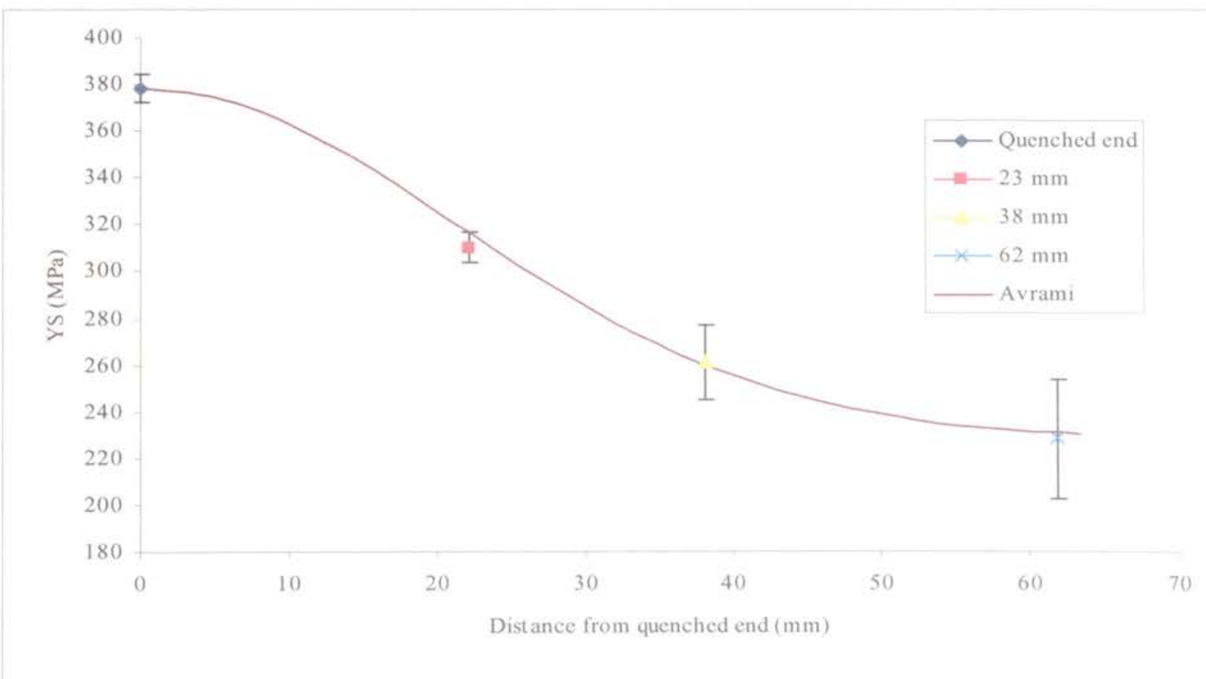



Figure 4.12. Variation of YS with Jominy distance for 7075 with 120-hr delay

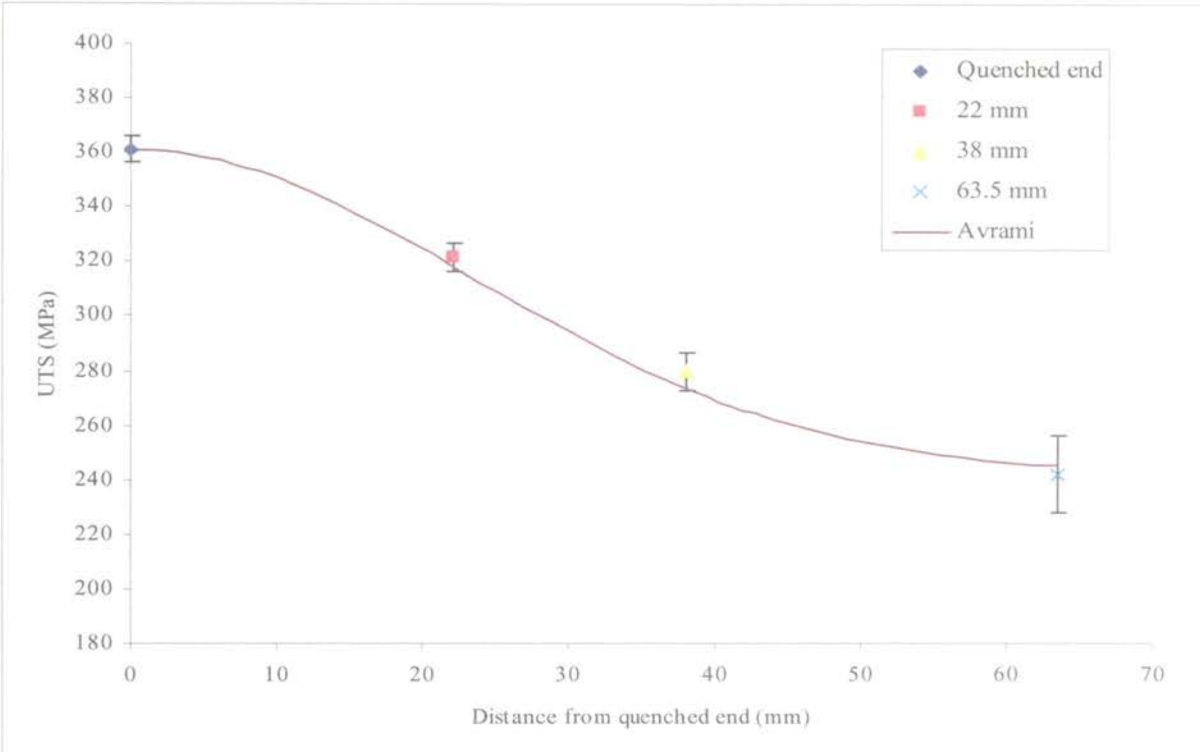



Figure 4.13. Variation of UTS with Jominy distance for 6061 with 1-hr delay

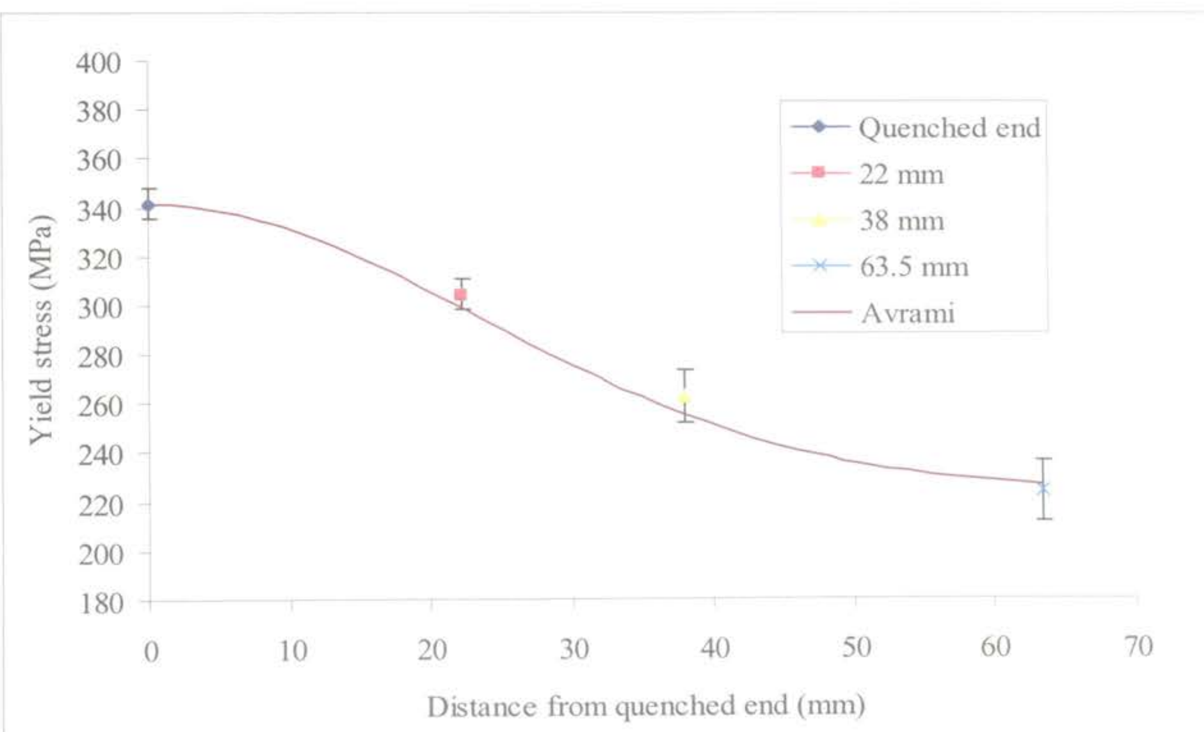



Figure 4.14. Variation of YS with Jominy Distance for 6061 with 1-hr delay

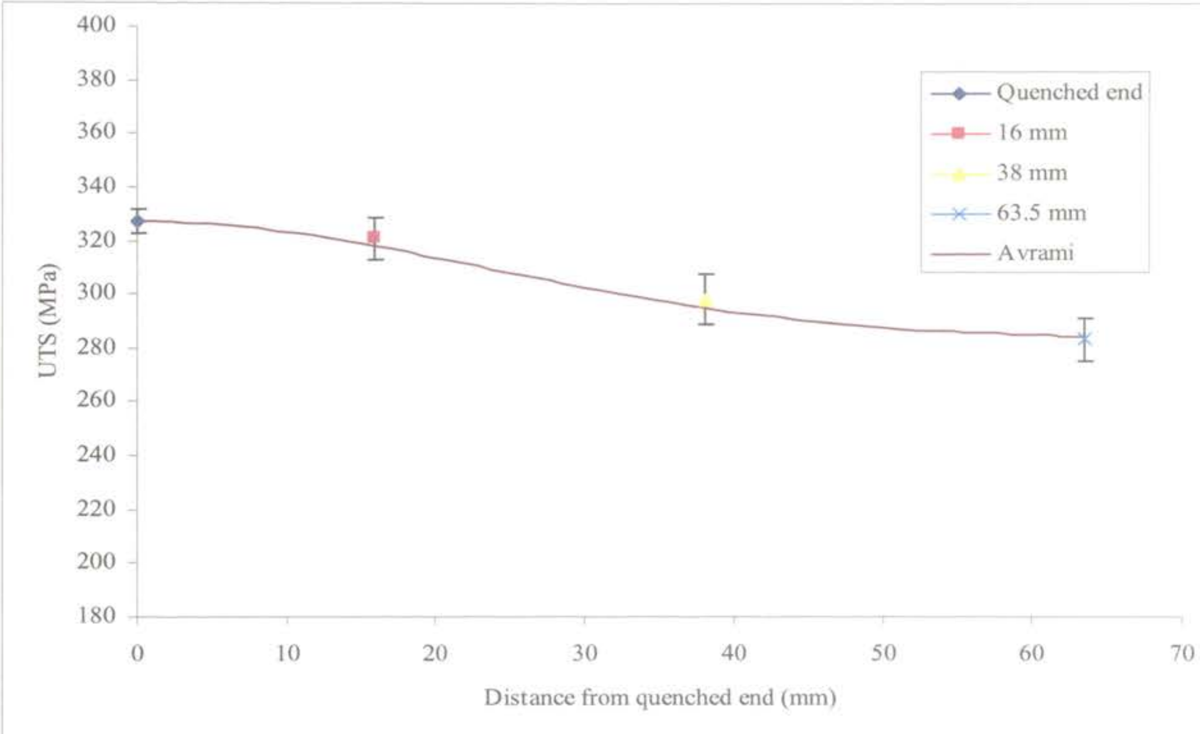



Figure 4.15. Variation of UTS with Jominy Distance for 6061 with 120-hr delay

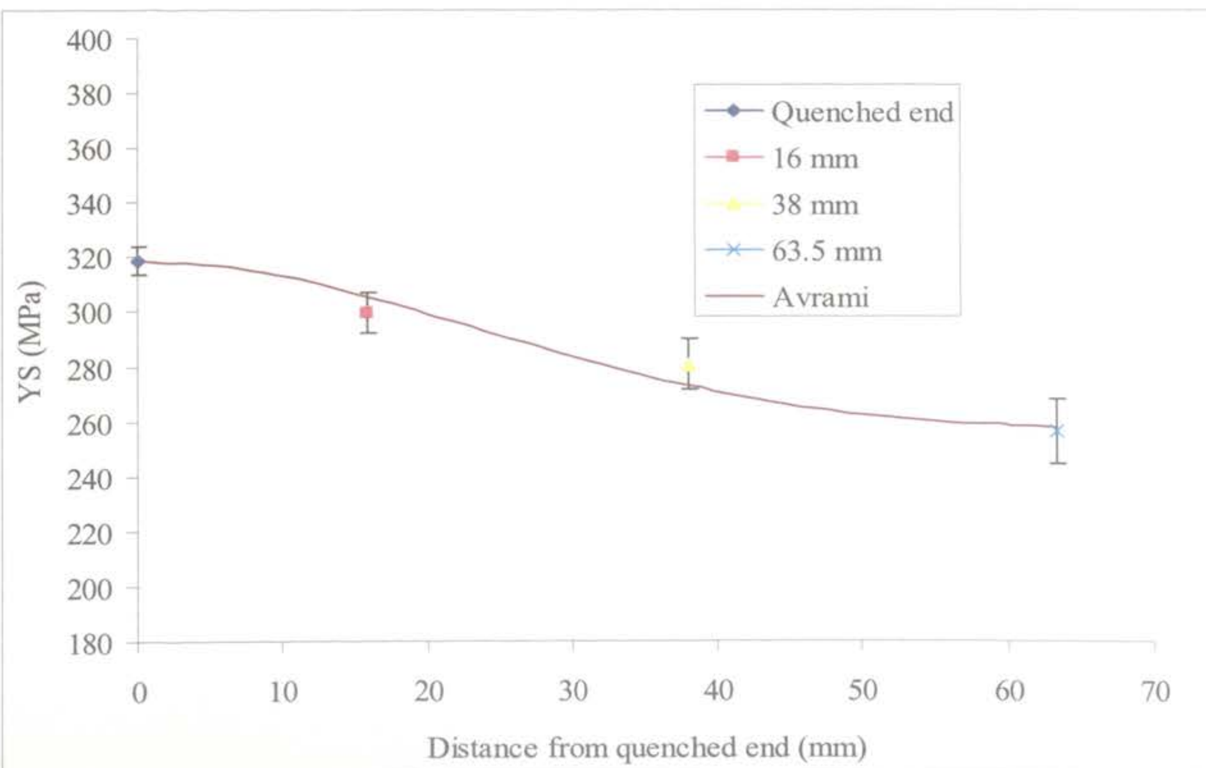



Figure 4.16. Variation of YS with Jominy Distance for 6061 with 120-hr delay

The strength curves for both the data and the Avrami fit are shown in Figures 4.9 through 4.16. The graphs clearly show that the Avrami exponent n and time dependent constant k obtained from the hardness values are accurate. Figures 4.9 through 4.16 also show the typical values of UTS and YS for different heat treatments of 7075 and 6061 wrought alloys. As noted above, using strength as the property to be determined, the Avrami relationship can be expressed in terms of strength as

$$\sigma(x) = \sigma_{\max} - \Delta\sigma(1 - \exp(-kx)^n)$$

where $\sigma(x)$ is the strength at a point x from the quenched end, $\sigma_{max}$ is the maximum strength, $\Delta\sigma$ is the difference between the maximum and minimum strength, k is the Avrami constant, and n is the Avrami exponent.

Figures 4.17 through 4.24 show the variation of UTS and YS for cast alloys. The experimental values are shown as points, and the theoretical Avrami curve for strength is shown. The value of $\sigma_{min}$ of the fit clearly does not match the experimental value, although it is in the error bar range of the experimental value.The deviation of the fit value is calculated for both UTS and YS of wrought and cast alloys. The error values are shown in Tables 4.7 through 4.10; in all cases they are less than 5%.

Table 4.7. Deviation of Avrami fit for UTS from experimental values for wrought alloys

| Alloy | $\sigma_{min}$ | $\sigma_{min}$ (fit) | $\sigma_{min}$(fit)-$\sigma_{min}$ | Error (%) |
|---|---|---|---|---|
| 7075 1hr delay | 200.4 | 207.28 | 6.88 | 3.43 |
| 7075 120 hr delay | 242.8 | 249.06 | 6.26 | 2.58 |
| 6061 1 hr delay | 242.4 | 245.3 | 2.9 | 1.20 |
| 6061 120 hr delay | 283.4 | 284.49 | 1.09 | 0.38 |

Table 4.8. Deviation of Avrami fit for UTS from experimental values for cast alloys

| Alloy | $\sigma_{min}$ | $\sigma_{min}$ (fit) | $\sigma_{min}$(fit)- $\sigma_{min}$ | Error (%) |
|---|---|---|---|---|
| A356 1 hr delay | 300 | 303.16 | 3.16 | 1.05 |
| A356 120 hr delay | 315 | 317.85 | 2.85 | 0.90 |
| B319 1 hr delay | 295 | 305.08 | 10.08 | 3.42 |
| B319 120 hr delay | 320 | 328.4 | 8.4 | 2.62 |

Table 4.9. Deviation of Avrami fit for YS from experimental values for wrought alloys

| Alloy | $\sigma_{min}$ | $\sigma_{min}$ (fit) | $\sigma_{min}$ (fit)- $\sigma_{min}$ | Error (%) |
|---|---|---|---|---|
| 7075 1 hr delay | 190 | 196.91 | 6.91 | 3.64 |
| 7075 120 hr delay | 228.3 | 234.65 | 6.35 | 2.78 |
| 6061 1 hr delay | 223.7 | 226.65 | 2.95 | 1.32 |
| 6061 120hr delay | 256.13 | 257.69 | 1.56 | 0.61 |

Table 4.10. Deviation of Avrami fit for YS from experimental values for cast alloys

| Alloy | $\sigma_{min}$ | $\sigma_{min}$ (fit) | $\sigma_{min}$ (fit)- $\sigma_{min}$ | Error (%) |
|---|---|---|---|---|
| A356 1 hr delay | 225 | 228.16 | 3.16 | 1.40 |
| A356 120 hr delay | 190 | 193.79 | 3.79 | 1.99 |
| B319 1 hr delay | 230 | 239.5 | 9.5 | 4.13 |
| B319 120 hr delay | 250 | 255.06 | 5.06 | 2.02 |

This analysis can be used to predict the values of strength if the values of $\sigma_{max}$ and $\Delta\sigma$ across a cross section to be heat treated are known. The error value can be eliminated by taking a sample at a higher value of Jominy length. This study has successfully developed a tensile testing method for Jominy samples, overcoming the problems experienced in previous studies [30].

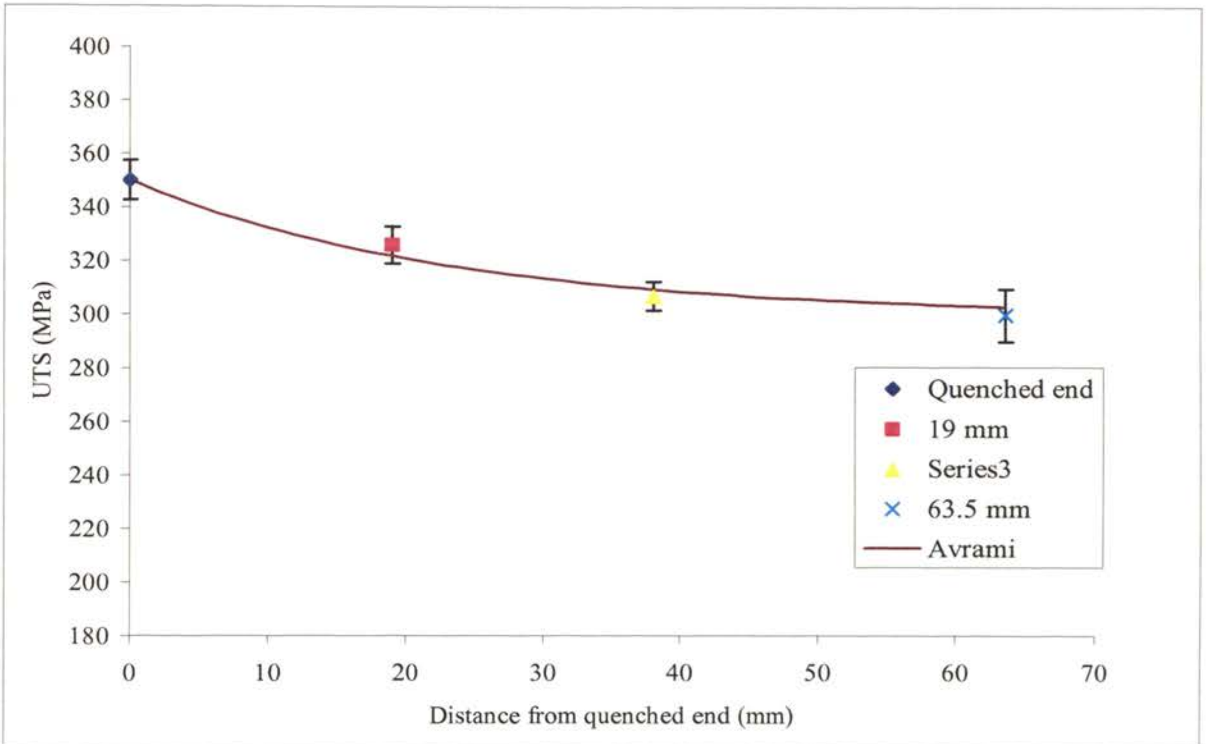



Figure 4.17. Variation of UTS with Jominy distance for A356 with 1-hr delay

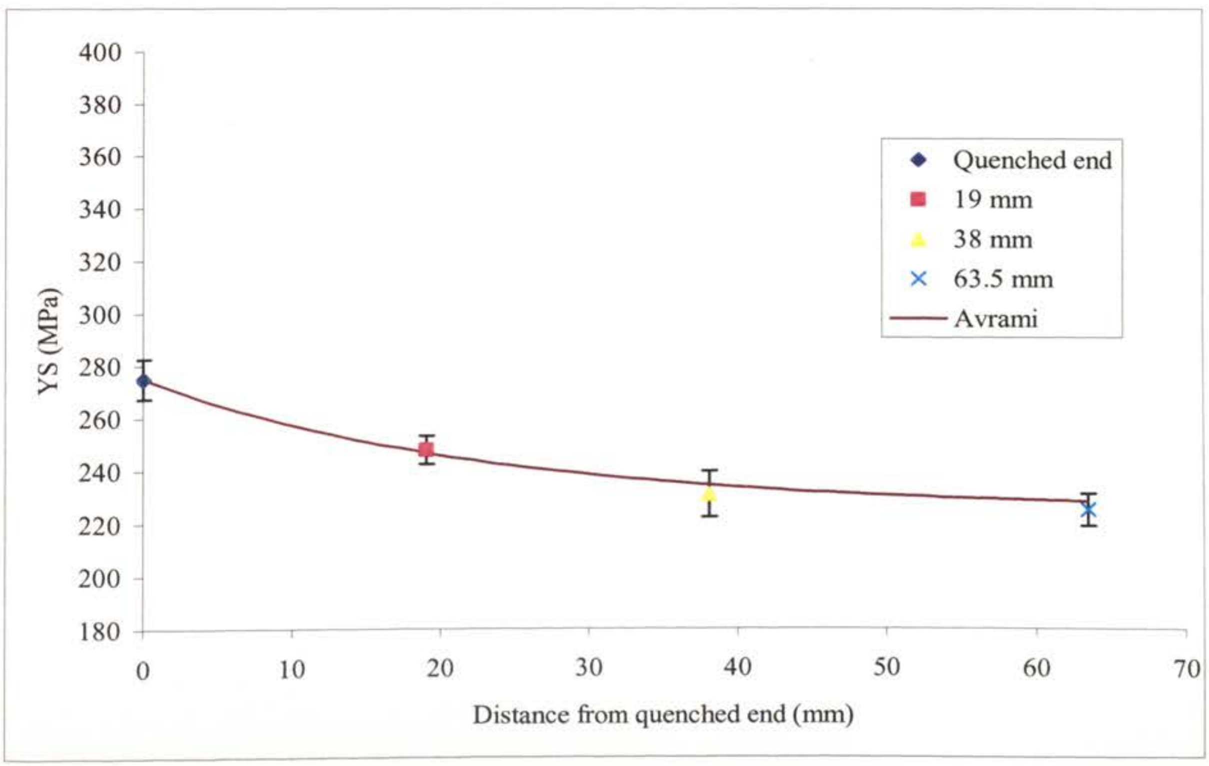



Figure 4.18. Variation of YS with Jominy distance for A356 with 1-hr delay

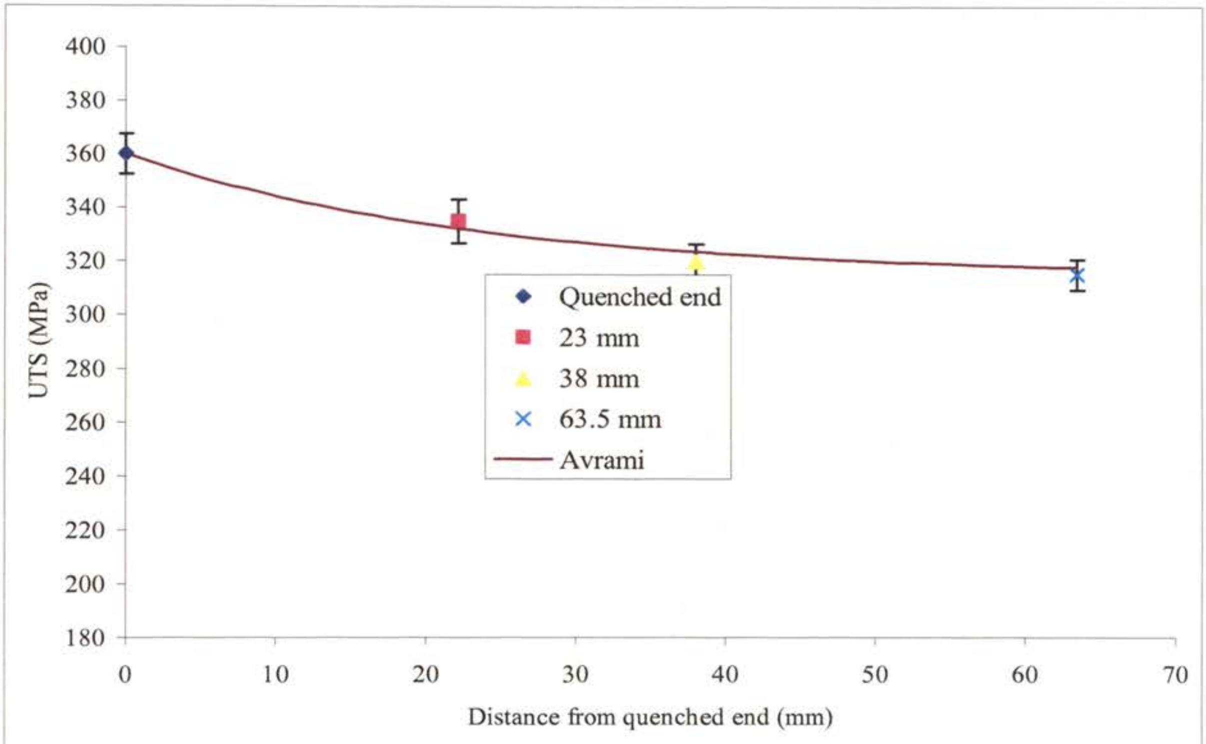



Figure 4.19. Variation of UTS with Jominy distance for A356 with 120-hr delay

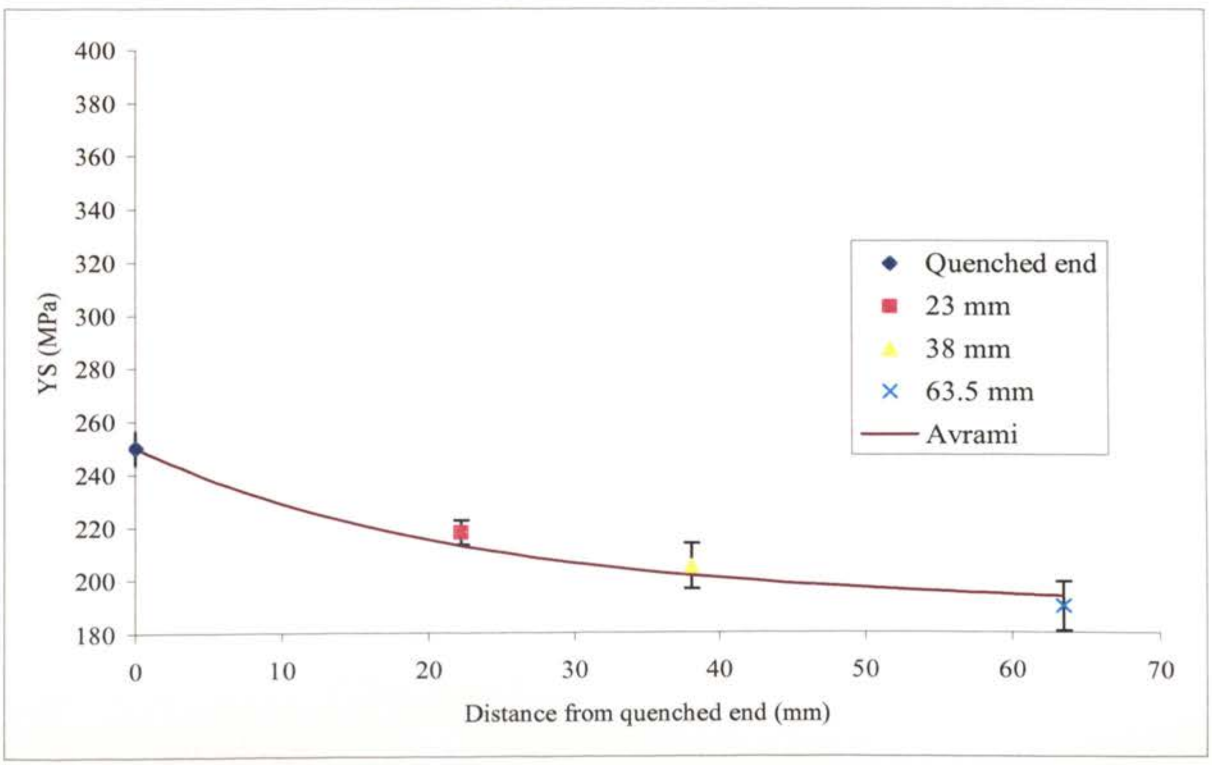



Figure 4.20. Variation of YS with Jominy distance for A356 with 120-hr delay

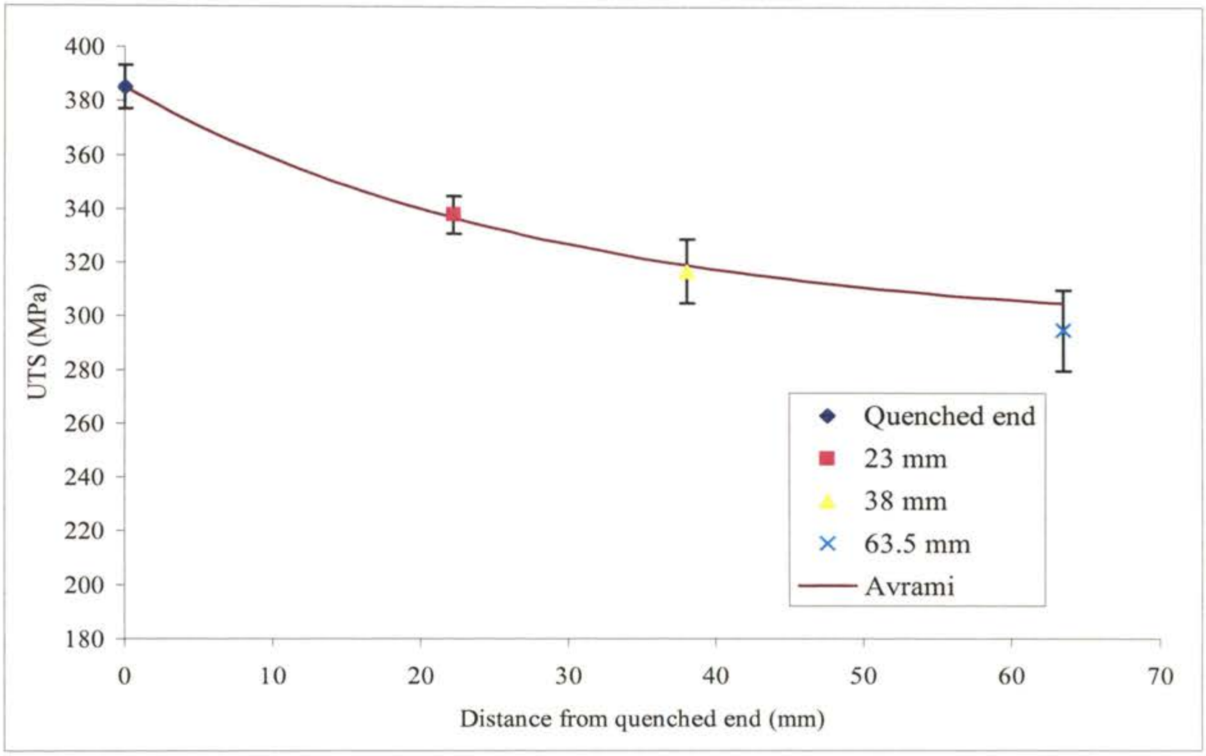



Figure 4.21. Variation of UTS with Jominy distance for with B319 1-hr delay

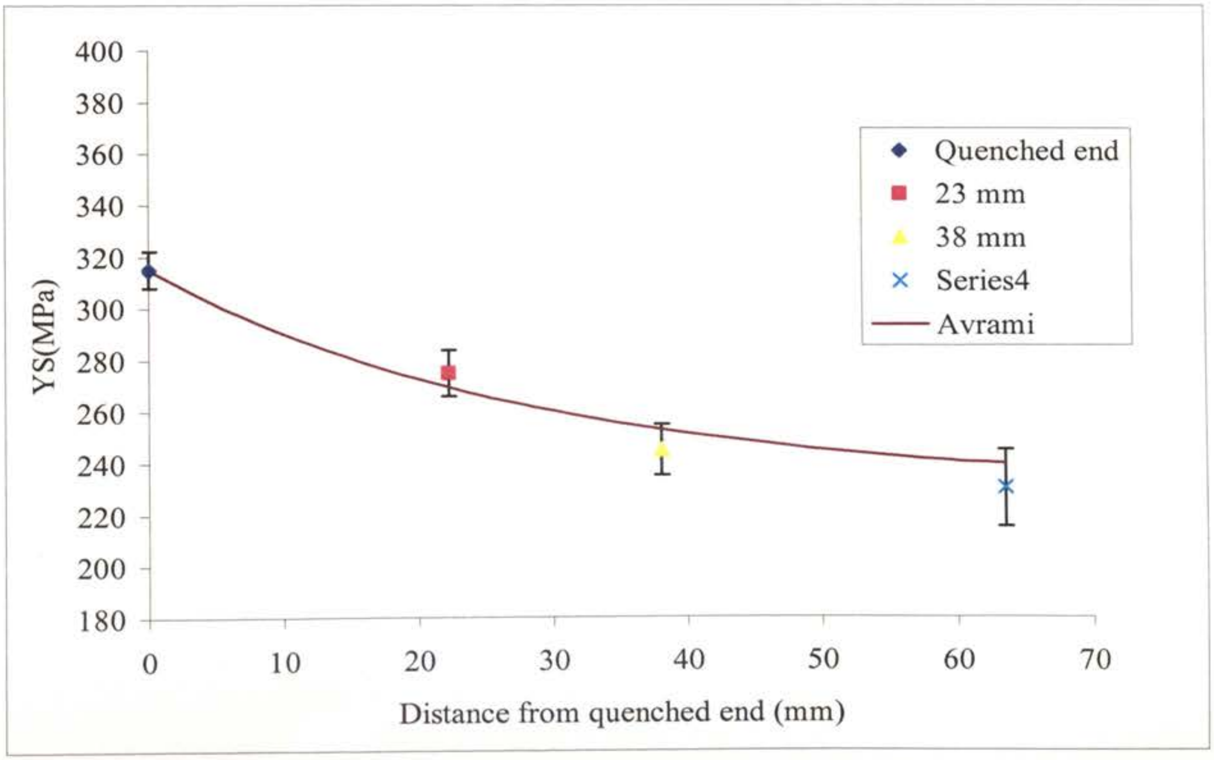



Figure 4.22. Variation of YS with Jominy distance for B319 with 1-hr delay

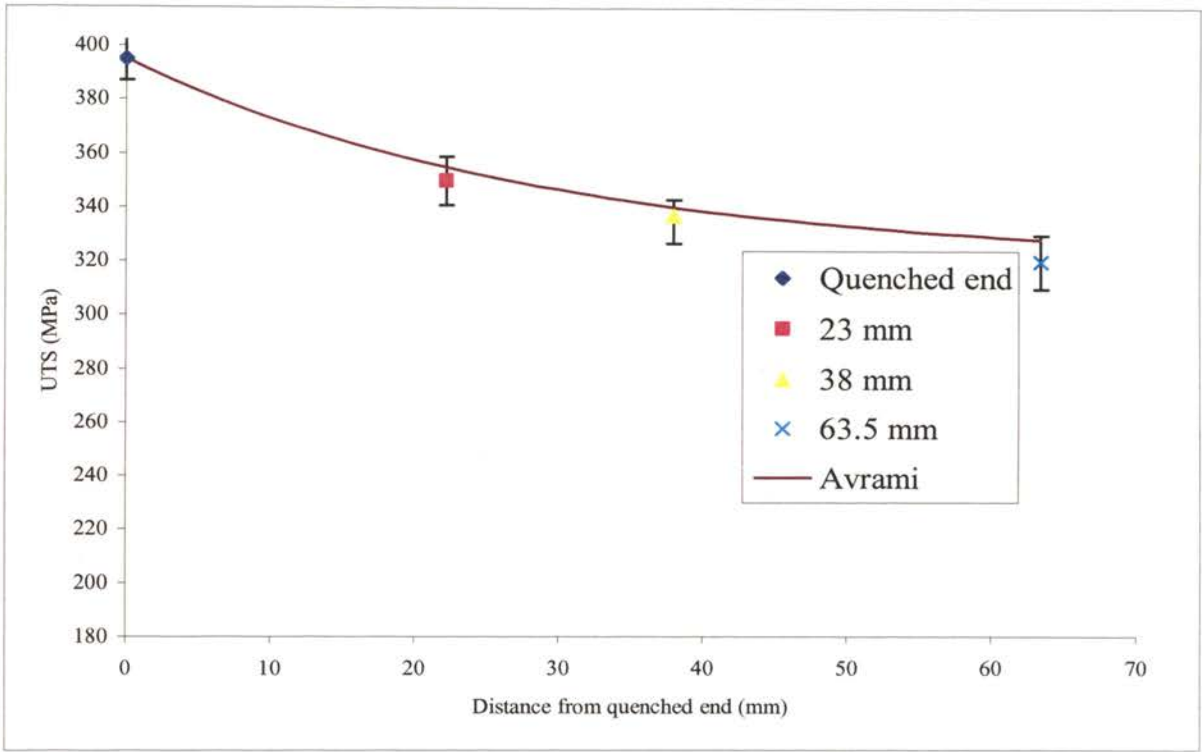



Figure 4.23. Variation of UTS with Jominy distance for B319 with 120-hr delay

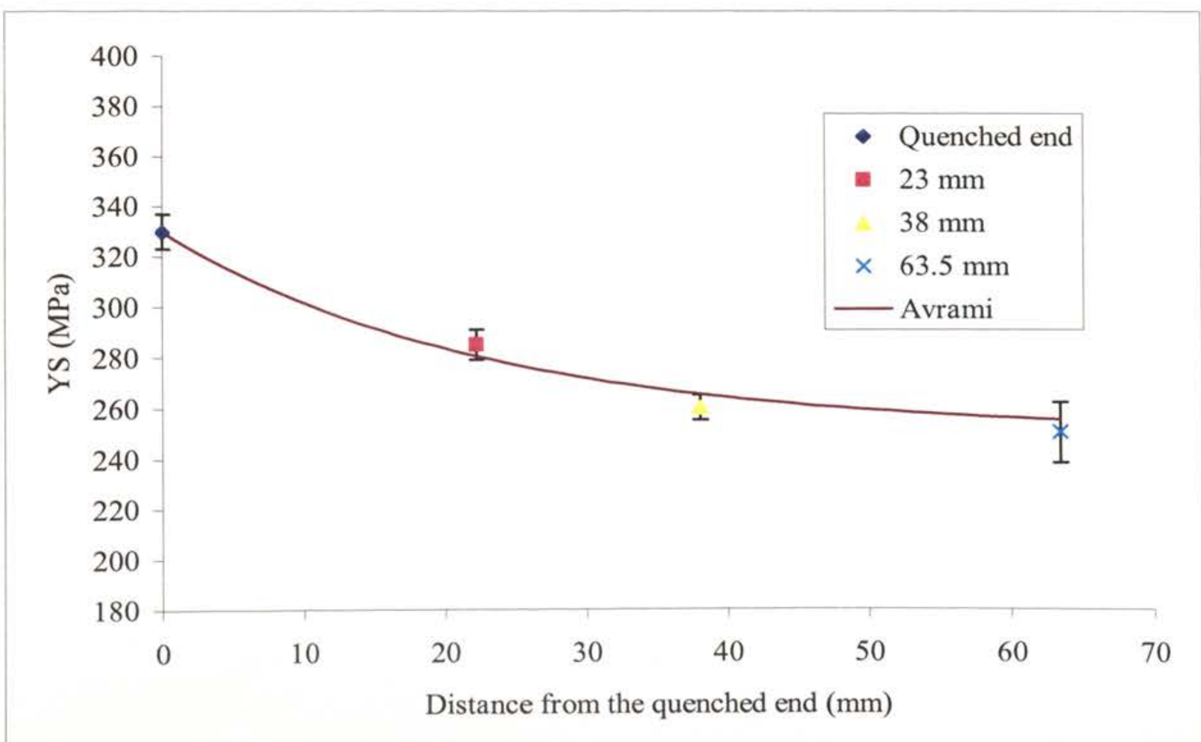



Figure 4.24. Variation of YS with Jominy distance for B319 with 120-hr delay

## 4.3. QUENCH FACTOR ANALYSIS

As explained in section 2.6, quench factors were calculated at various points along the Jominy bar. The incremental times shown in equation 2-7 were calculated from cooling curves simulated as described in section 3.5. Using the values of $\Delta t_1$, $\Delta t_2$, $\Delta t_3$, etc. and the values of $\tau_1$, $\tau_2$, $\tau_3$, etc, equation 2-7 can be solved with MATLAB to obtain the values of $C_t$ at various temperatures. Plotting the temperature versus log $C_t$ plots generates the C-curves, which are shown in Figures 4-25 through 4-28 for the various alloys studied here. The C-curves show that for alloys 7075, 6061, A356, and B319 the nose is at the same temperature, and the sample with the longer delay before aging has a lower $C_t$ value at that temperature. The C-curves were generated assuming 0.5% transformation that is 99.5% is untransformed during quenching.

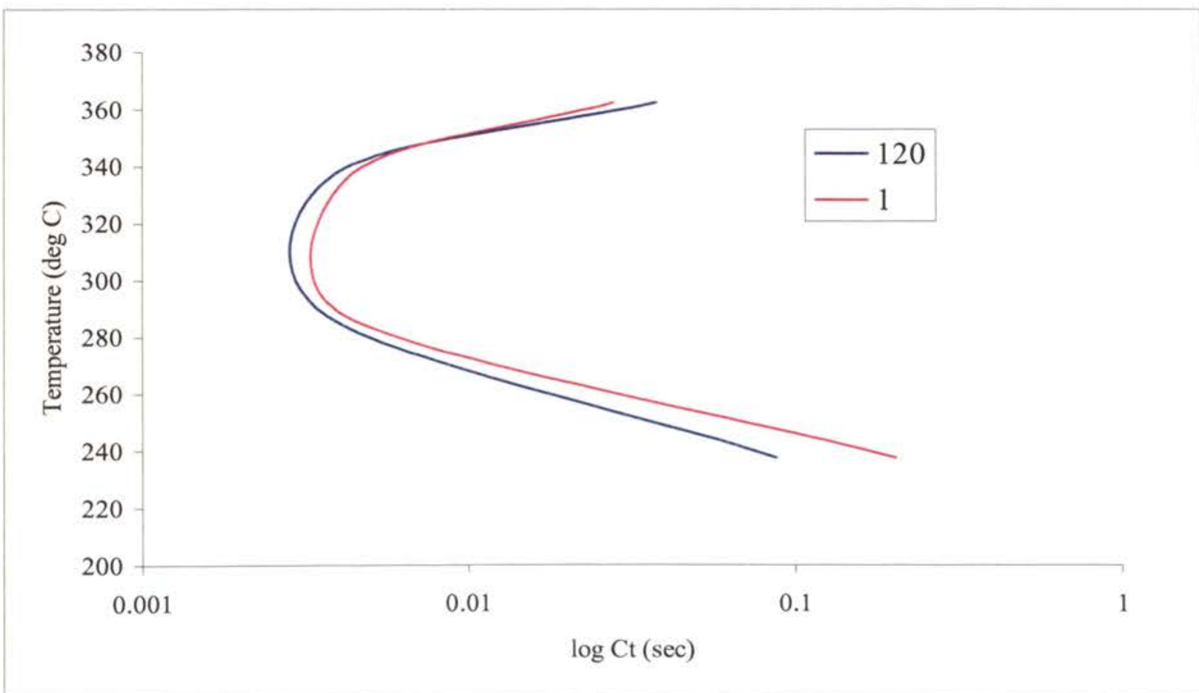



Figure 4.25. C-curve for 7075 T6 temper

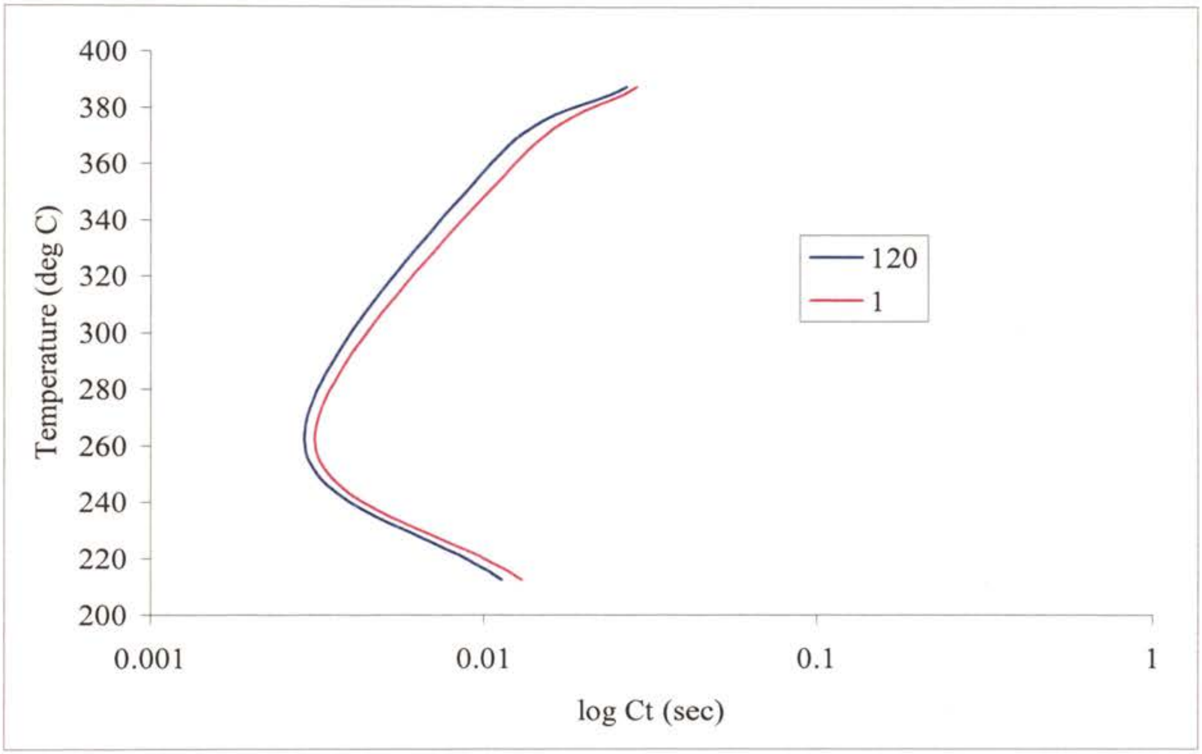



Figure 4.26. C-curve for 6061 T6 temper.

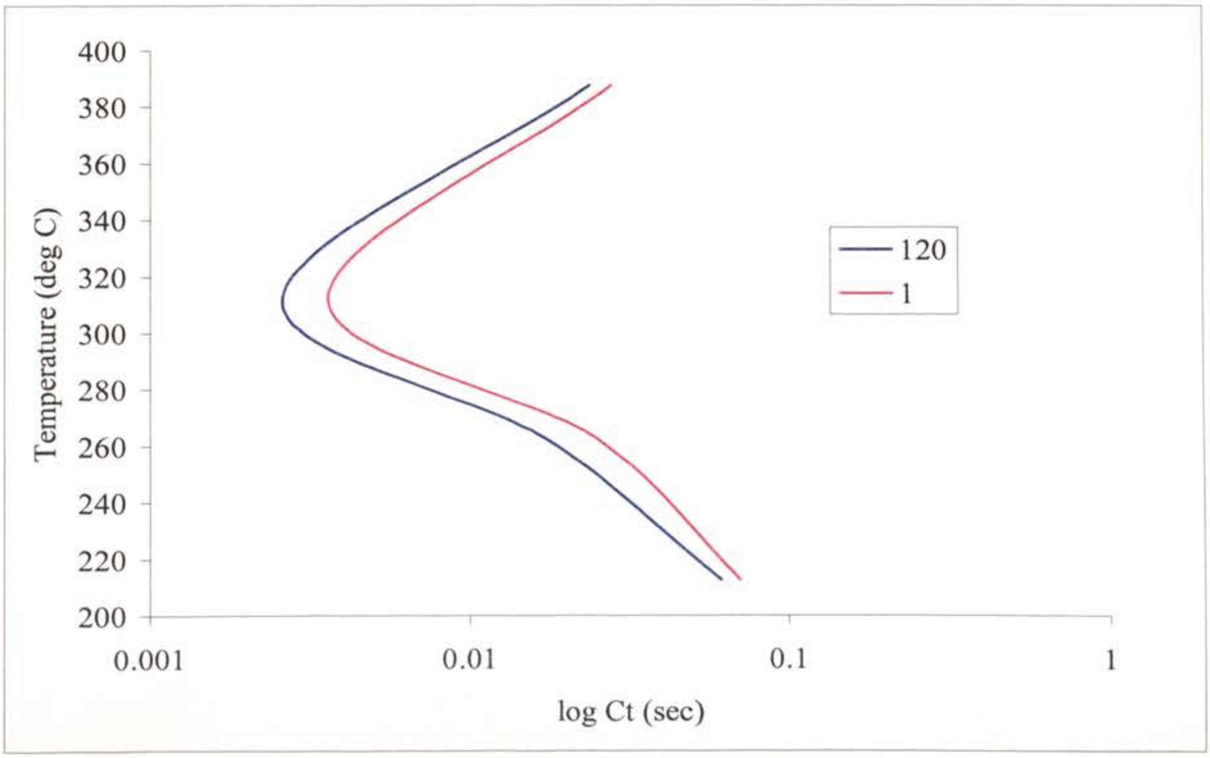



Figure 4.27. C-curve for A356 T6 temper

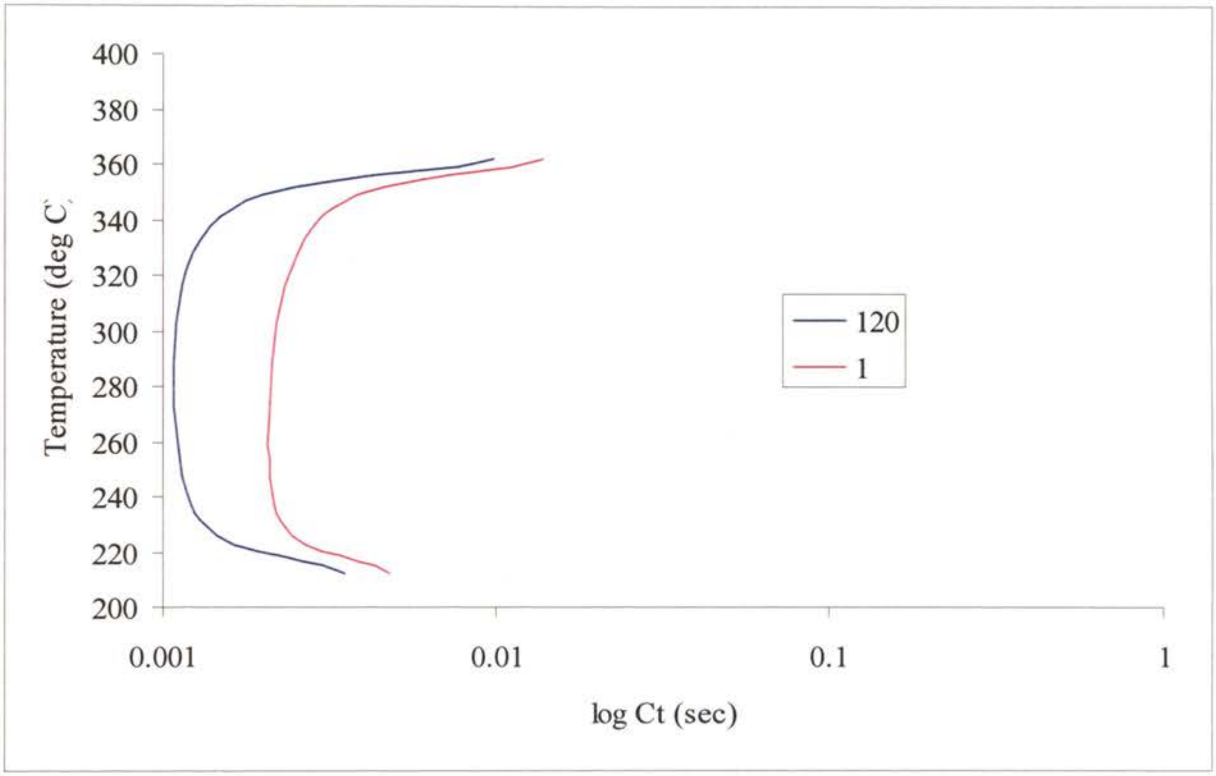



Figure 4.28. C-curve for B319 T6 temper.

Figures 4-27 and 4-28 clearly indicate that the critical cooling rate at the critical temperature range for B 319 is greater than that for A356, which confirms the findings of previous studies [21]. Also, the critical cooling rate of 7075 is higher than that of 6061, and the critical cooling rate of B319 is higher than that of A356.

Using equation 2-8 calculated quench factors can be used to determine properties.

# 5. CONCLUSIONS

This work has established a methodology for determining C-curves using the JEQ test, Avrami parameters, and quench factors. The equations related to the quench factors are discussed in section 2.6., and MATLAB was used to solve the set of nonlinear equations. Cooling in the Jominy bar was successfully modeled using FLUENT. Cooling curves were simulated at various locations using convective heat transfer coefficient values from previous studies and confirmed by experiment.

This work has also validated an approach to determine accurate values of Avrami parameters. Previous studies used a trend curve to fit the Avrami parameters to the hardness values. This study proposes a mathematical procedure to calculate the Avrami parameters accurately. The values of k and n were the same for an alloy irrespective of the delay before aging. This observation proves that the critical times will be the same for nucleation and growth of the precipitates and for growth morphology of the precipitates.

This work has also developed a methodology to measure tensile properties as a function of quench rate using mini tensile samples. Samples taken from various points defined the curve and Avrami relationship generates the tensile strength Therefore, this method can reproduce tensile values along a thick section with few experiments.

$H_{max}$ was found to be higher in case of longer delay times for all the alloys, irrespective of the heat treatment.

In the case of wrought and cast alloys, the critical temperature for the nose is the same, but the time is different. This indicates that the critical temperature for transformation is the same, but the time for transformation varies with the delay before aging.

# 6. FUTURE WORK

- Try to build the C-curves using more points.
- Writing an automated program to produce the C-curves from the hardness and cooling curve data.
- Rectify the problem encountered in mini tensile testing with the minimum strength value.
- Extend this work to other commercial aluminum alloys.

# APPENDIX A

# HARDNESS VALUES

Table 1 Hardness values and calculations for 7075 1hr delay

| distance | hardness | H max | 85.60 | H(x)-Hmin | fit | K1 | ln(H/Hmax) | | H/Hmax | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 85.60 | H min | 53.00 | 32.60 | 85.60 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 | |
| 2.00 | 85.00 | del H | 32.60 | 32.00 | 85.39 | -0.01 | -0.01 | 1.40 | 0.99 | 3.18 | 1.16 |
| 3.00 | 85.00 | k | 0.03 | 32.00 | 85.10 | | -0.01 | 1.40 | 0.99 | 4.76 | 1.56 |
| 4.00 | 85.00 | n | 2.08 | 32.00 | 84.70 | | -0.01 | 1.40 | 0.99 | 6.35 | 1.85 |
| 5.00 | 84.00 | | | 31.00 | 84.19 | | -0.02 | 3.76 | 0.98 | 7.94 | 2.07 |
| 6.00 | 84.00 | | 0.03 | 31.00 | 83.56 | | -0.02 | 3.76 | 0.98 | 9.53 | 2.25 |
| 7.00 | 83.00 | | | 30.00 | 82.82 | | -0.03 | 6.15 | 0.97 | 11.11 | 2.41 |
| 8.00 | 83.00 | | | 30.00 | 81.98 | | -0.03 | 6.15 | 0.97 | 12.70 | 2.54 |
| 9.00 | 82.00 | | | 29.00 | 81.04 | | -0.04 | 8.57 | 0.96 | 14.29 | 2.66 |
| 10.00 | 81.00 | | | 28.00 | 80.03 | | -0.06 | 11.02 | 0.95 | 15.88 | 2.76 |
| 11.00 | 80.00 | | | 27.00 | 78.94 | | -0.07 | 13.50 | 0.93 | 17.46 | 2.86 |
| 12.00 | 79.00 | | | 26.00 | 77.79 | | -0.08 | 16.01 | 0.92 | 19.05 | 2.95 |
| 13.00 | 78.00 | | | 25.00 | 76.59 | | -0.09 | 18.55 | 0.91 | 20.64 | 3.03 |
| 14.00 | 76.00 | | | 23.00 | 75.35 | | -0.12 | 23.73 | 0.89 | 22.23 | 3.10 |
| 15.00 | 76.00 | | | 23.00 | 74.09 | | -0.12 | 23.73 | 0.89 | 23.81 | 3.17 |
| 16.00 | 74.00 | | | 21.00 | 72.81 | | -0.15 | 29.05 | 0.86 | 25.40 | 3.23 |
| 17.00 | 73.00 | | | 20.00 | 71.53 | | -0.16 | 31.77 | 0.85 | 26.99 | 3.30 |
| 18.00 | 71.00 | | | 18.00 | 70.25 | | -0.19 | 37.31 | 0.83 | 28.58 | 3.35 |
| 19.00 | 71.00 | | | 18.00 | 68.99 | | -0.19 | 37.31 | 0.83 | 30.16 | 3.41 |
| 20.00 | 70.00 | | | 17.00 | 67.76 | | -0.20 | 40.14 | 0.82 | 31.75 | 3.46 |
| 21.00 | 67.00 | | | 14.00 | 66.56 | | -0.24 | 48.88 | 0.78 | 33.34 | 3.51 |
| 22.00 | 65.00 | | | 12.00 | 65.40 | | -0.28 | 54.92 | 0.76 | 34.93 | 3.55 |
| 23.00 | 64.00 | | | 11.00 | 64.30 | | -0.29 | 58.01 | 0.75 | 36.51 | 3.60 |
| 24.00 | 63.00 | | | 10.00 | 63.24 | | -0.31 | 61.16 | 0.74 | 38.10 | 3.64 |
| 25.00 | 61.00 | | | 8.00 | 62.24 | | -0.34 | 67.59 | 0.71 | 39.69 | 3.68 |
| 26.00 | 62.00 | | | 9.00 | 61.30 | | -0.32 | 64.35 | 0.72 | 41.28 | 3.72 |
| 27.00 | 60.00 | | | 7.00 | 60.43 | | -0.36 | 70.89 | 0.70 | 42.86 | 3.76 |
| 28.00 | 58.00 | | | 5.00 | 59.61 | | -0.39 | 77.65 | 0.68 | 44.45 | 3.79 |
| 29.00 | 58.00 | | | 5.00 | 58.86 | | -0.39 | 77.65 | 0.68 | 46.04 | 3.83 |
| 30.00 | 57.00 | | | 4.00 | 58.17 | | -0.41 | 81.12 | 0.67 | 47.63 | 3.86 |
| 31.00 | 56.00 | | | 3.00 | 57.54 | | -0.42 | 84.65 | 0.65 | 49.21 | 3.90 |
| 32.00 | 56.00 | | | 3.00 | 56.97 | | -0.42 | 84.65 | 0.65 | 50.80 | 3.93 |
| 33.00 | 55.00 | | | 2.00 | 56.45 | | -0.44 | 88.25 | 0.64 | 52.39 | 3.96 |
| 34.00 | 55.00 | | | 2.00 | 55.99 | | -0.44 | 88.25 | 0.64 | 53.98 | 3.99 |
| 35.00 | 55.00 | | | 2.00 | 55.58 | | -0.44 | 88.25 | 0.64 | 55.56 | 4.02 |
| 36.00 | 54.00 | | | 1.00 | 55.21 | | -0.46 | 91.91 | 0.63 | 57.15 | 4.05 |
| 37.00 | 54.00 | | | 1.00 | 54.89 | | -0.46 | 91.91 | 0.63 | 58.74 | 4.07 |
| 38.00 | 53.00 | | | 0.00 | 54.60 | | -0.48 | 95.64 | 0.62 | 60.33 | 4.10 |
| 39.00 | 53.00 | | | 0.00 | 54.36 | | -0.48 | 95.64 | 0.62 | 61.91 | 4.13 |
| 40.00 | 53.00 | | | 0.00 | 54.14 | | -0.48 | 95.64 | 0.62 | 63.50 | 4.15 |

Table 2 Hardness values and calculations for 7075 120 hr delay

| distance | | hardness | | | | | | fit | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 85.6 | 87.8 | H max | 87.8 | H(x)-H min | ln G | ln A | 87.8 | 0 | 0.0 |
| 2 | 85 | 87 | H min | 55 | 32 | -3.70125 | 0.693147 | 87.53511 | -0.00811 | 3.2 |
| 3 | 85 | 87 | del H | 32.8 | 32 | -3.70125 | 1.098612 | 87.20953 | -0.01817 | 4.8 |
| 4 | 85 | 87 | | | 32 | -3.70125 | 1.386294 | 86.76076 | -0.0322 | 6.4 |
| 5 | 84 | 86 | k | 0.028 | 31 | -2.87455 | 1.609438 | 86.19443 | -0.05019 | 7.9 |
| 6 | 84 | 86 | n | 2.0 | 31 | -2.87455 | 1.791759 | 85.51737 | -0.07213 | 9.5 |
| 7 | 83 | 85 | | | 30 | -2.41653 | 1.94591 | 84.73749 | -0.09802 | 11.1 |
| 8 | 83 | 85 | | 0.028 | 30 | -2.41653 | 2.079442 | 83.86367 | -0.12784 | 12.7 |
| 9 | 82 | 84 | | | 29 | -2.09449 | 2.197225 | 82.90558 | -0.1616 | 14.3 |
| 10 | 81 | 83 | | | 28 | -1.84374 | 2.302585 | 81.87356 | -0.19929 | 15.9 |
| 11 | 80 | 82 | | | 27 | -1.63685 | 2.397895 | 80.77838 | -0.24089 | 17.5 |
| 12 | 79 | 81 | | | 26 | -1.45959 | 2.484907 | 79.63113 | -0.28642 | 19.1 |
| 13 | 78 | 80 | | | 25 | -1.3036 | 2.564949 | 78.44298 | -0.33586 | 20.6 |
| 14 | 76 | 78 | | | 23 | -1.03582 | 2.639057 | 77.22503 | -0.38921 | 22.2 |
| 15 | 76 | 78 | | | 23 | -1.03582 | 2.70805 | 75.98817 | -0.44647 | 23.8 |
| 16 | 74 | 76 | | | 21 | -0.80765 | 2.772589 | 74.74287 | -0.50764 | 25.4 |
| 17 | 73 | 75 | | | 20 | -0.70381 | 2.833213 | 73.49912 | -0.57271 | 27.0 |
| 18 | 71 | 73 | | | 18 | -0.51073 | 2.890372 | 72.26624 | -0.64168 | 28.6 |
| 19 | 71 | 73 | | | 18 | -0.51073 | 2.944439 | 71.05283 | -0.71454 | 30.2 |
| 20 | 70 | 72 | | | 17 | -0.41974 | 2.995732 | 69.86666 | -0.79131 | 31.8 |
| 21 | 67 | 69 | | | 14 | -0.16091 | 3.044522 | 68.71463 | -0.87197 | 33.3 |
| 22 | 65 | 67 | | | 12 | 0.005507 | 3.091042 | 67.60273 | -0.95651 | 34.9 |
| 23 | 64 | 66 | | | 11 | 0.088499 | 3.135494 | 66.53601 | -1.04495 | 36.5 |
| 24 | 63 | 65 | | | 10 | 0.172139 | 3.178054 | 65.51861 | -1.13728 | 38.1 |
| 25 | 61 | 63 | | | 8 | 0.344289 | 3.218876 | 64.55373 | -1.2335 | 39.7 |
| 26 | 62 | 64 | | | 9 | 0.257123 | 3.258097 | 63.64372 | -1.3336 | 41.3 |
| 27 | 60 | 62 | | | 7 | 0.434712 | 3.295837 | 62.79008 | -1.43758 | 42.9 |
| 28 | 58 | 60 | | | 5 | 0.631799 | 3.332205 | 61.99355 | -1.54544 | 44.5 |
| 29 | 58 | 60 | | | 5 | 0.631799 | 3.367296 | 61.25415 | -1.65718 | 46.0 |
| 30 | 57 | 59 | | | 4 | 0.743904 | 3.401197 | 60.57127 | -1.77281 | 47.6 |
| 31 | 56 | 58 | | | 3 | 0.872053 | 3.433987 | 59.94375 | -1.8923 | 49.2 |
| 32 | 56 | 58 | | | 3 | 0.872053 | 3.465736 | 59.36994 | -2.01568 | 50.8 |
| 33 | 55 | 57 | | | 2 | 1.028648 | 3.496508 | 58.84779 | -2.14293 | 52.4 |
| 34 | 55 | 57 | | | 2 | 1.028648 | 3.526361 | 58.37494 | -2.27405 | 54.0 |
| 35 | 55 | 57 | | | 2 | 1.028648 | 3.555348 | 57.94875 | -2.40905 | 55.6 |
| 36 | 54 | 56 | | | 1 | 1.250025 | 3.583519 | 57.56643 | -2.54791 | 57.2 |
| 37 | 54 | 56 | | | 1 | 1.250025 | 3.610918 | 57.22506 | -2.69065 | 58.7 |
| 38 | 53 | 55 | | | 0 | | | 56.92164 | -2.83725 | 60.3 |
| 39 | 53 | 55 | | | 0 | | | 56.65319 | -2.98772 | 61.9 |
| 40 | 53 | 55 | | | 0 | | | 56.41676 | -3.14206 | 63.5 |

Table 3 Hardness values for 6061 1hr delay

| position | H1 | H2 | Havg | | | H(x)-Hmin | ln X | fit |
|---|---|---|---|---|---|---|---|---|
| 0 | 64 | 63.3 | 63.65 | H max | 63.65 | 15.65 | | 63.65 |
| 2 | 62 | 60 | 63.5 | H min | 48 | 15.5 | 0.693147 | 63.49979 |
| 3 | 61.5 | 62 | 63 | del H | 15.65 | 15 | 1.098612 | 63.31406 |
| 4 | 61 | 61 | 63 | | | 15 | 1.386294 | 63.05777 |
| 5 | 61 | 61.5 | 62.5 | K | 0.031 | 14.5 | 1.609438 | 62.73454 |
| 6 | 61 | 61 | 62 | N | 2 | 14 | 1.791759 | 62.34889 |
| 7 | 61 | 61 | 62 | | | 14 | 1.94591 | 61.90612 |
| 8 | 61 | 61 | 61 | | | 13 | 2.079442 | 61.41218 |
| 9 | 60.5 | 60.5 | 60.5 | | | 12.5 | 2.197225 | 60.87355 |
| 10 | 60 | 59 | 59.5 | K1 | -0.00501 | 11.5 | 2.302585 | 60.29712 |
| 11 | 59.5 | 59 | 59.25 | | | 11.25 | 2.397895 | 59.68999 |
| 12 | 59.5 | 59 | 59.25 | | | 11.25 | 2.484907 | 59.05937 |
| 13 | 58 | 59 | 58.5 | | | 10.5 | 2.564949 | 58.41245 |
| 14 | 58 | 58.5 | 58.25 | | | 10.25 | 2.639057 | 57.7562 |
| 15 | 57 | 58 | 57.5 | | | 9.5 | 2.70805 | 57.09734 |
| 16 | 57 | 58 | 57.5 | | | 9.5 | 2.772589 | 56.44217 |
| 17 | 57 | 57 | 57 | | | 9 | 2.833213 | 55.7965 |
| 18 | 57.5 | 56 | 56.75 | | | 8.75 | 2.890372 | 55.16557 |
| 19 | 55 | 55 | 55 | | | 7 | 2.944439 | 54.55402 |
| 20 | 53.5 | 54 | 53.75 | | | 5.75 | 2.995732 | 53.96582 |
| 21 | 53 | 53 | 53 | | | 5 | 3.044522 | 53.40429 |
| 22 | 53 | 52 | 52.5 | | | 4.5 | 3.091042 | 52.87206 |
| 23 | 52.5 | 53 | 52.75 | | | 4.75 | 3.135494 | 52.37112 |
| 24 | 52 | 52.5 | 52.25 | | | 4.25 | 3.178054 | 51.90282 |
| 25 | 51 | 52 | 51.5 | | | 3.5 | 3.218876 | 51.46793 |
| 26 | 51.5 | 52 | 51.75 | | | 3.75 | 3.258097 | 51.06668 |
| 27 | 51.5 | 51.5 | 51.5 | | | 3.5 | 3.295837 | 50.6988 |
| 28 | 50 | 50.5 | 50.25 | | | 2.25 | 3.332205 | 50.36363 |
| 29 | 49.5 | 50 | 49.75 | | | 1.75 | 3.367296 | 50.06013 |
| 30 | 49.5 | 49.5 | 49.5 | | | 1.5 | 3.401197 | 49.78696 |
| 31 | 48.5 | 50 | 49.25 | | | 1.25 | 3.433987 | 49.54256 |
| 32 | 49 | 49.5 | 49.25 | | | 1.25 | 3.465736 | 49.32518 |
| 33 | 48 | 50 | 49 | | | 1 | 3.496508 | 49.13295 |
| 34 | 48.5 | 49 | 48.75 | | | 0.75 | 3.526361 | 48.96395 |
| 35 | 49 | 49 | 49 | | | 1 | 3.555348 | 48.81621 |
| 36 | 48 | 49 | 48.5 | | | 0.5 | 3.583519 | 48.6878 |
| 37 | 48 | 48 | 48 | | | 0 | 3.610918 | 48.57679 |
| 38 | 48 | 48 | 48 | | | 0 | 3.637586 | 48.48138 |
| 39 | 48 | 48 | 48 | | | 0 | 3.663562 | 48.39982 |
| 40 | 48 | 48 | 48 | | | 0 | 3.688879 | 48.33047 |

Table 4 Hardness values for 6061 120 hr delay

| Distance | h1 | h2 | h | H max | 61.5 | H(x)-Hmin | ln I | ln X | fit |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 59 | 54.7 | 61.5 | H min | 46 | 15.5 | | | 61.5 |
| 2 | 56 | 53.5 | 61 | del H | 15.5 | 15 | -3.41764 | 0.693147 | 61.33776 |
| 3 | 56 | 54 | 61 | | | 15 | -3.41764 | 1.098612 | 61.13734 |
| 4 | 56 | 54 | 60.5 | k | 0.032 | 14.5 | -2.70768 | 1.386294 | 60.86114 |
| 5 | 55 | 54 | 60 | n | 2 | 14 | -2.28492 | 1.609438 | 60.51343 |
| 6 | 55 | 53 | 60 | | -0.00501 | 14 | -2.28492 | 1.791759 | 60.09948 |
| 7 | 56 | 54 | 59 | | | 13 | -1.73789 | 1.94591 | 59.62545 |
| 8 | 55 | 53 | 58.5 | | | 12.5 | -1.5366 | 2.079442 | 59.09827 |
| 9 | 54 | 53 | 57.5 | | | 11.5 | -1.20901 | 2.197225 | 58.52541 |
| 10 | 56 | 54 | 57.25 | | | 11.25 | -1.13796 | 2.302585 | 57.91476 |
| 11 | 56.5 | 53 | 57.25 | | | 11.25 | -1.13796 | 2.397895 | 57.2744 |
| 12 | 55 | 53 | 56.5 | | | 10.5 | -0.94298 | 2.484907 | 56.61248 |
| 13 | 54.5 | 52.5 | 56.25 | | | 10.25 | -0.88295 | 2.564949 | 55.937 |
| 14 | 53 | 53 | 55.5 | | | 9.5 | -0.71427 | 2.639057 | 55.25568 |
| 15 | 53 | 51 | 55.5 | | | 9.5 | -0.71427 | 2.70805 | 54.57585 |
| 16 | 53.5 | 51 | 55 | | | 9 | -0.60951 | 2.772589 | 53.90425 |
| 17 | 53 | 51 | 54.75 | | | 8.75 | -0.55899 | 2.833213 | 53.24702 |
| 18 | 53 | 50 | 53 | | | 7 | -0.2295 | 2.890372 | 52.60957 |
| 19 | 52 | 49 | 51.75 | | | 5.75 | -0.00839 | 2.944439 | 51.99656 |
| 20 | 52 | 47 | 51 | | | 5 | 0.123458 | 2.995732 | 51.41185 |
| 21 | 51 | 48 | 50.5 | | | 4.5 | 0.212497 | 3.044522 | 50.85853 |
| 22 | 51.5 | 47.5 | 50.75 | | | 4.75 | 0.167796 | 3.091042 | 50.33889 |
| 23 | 51 | 49 | 50.25 | | | 4.25 | 0.257677 | 3.135494 | 49.8545 |
| 24 | 51 | 48 | 49.5 | | | 3.5 | 0.397485 | 3.178054 | 49.40621 |
| 25 | 50 | 49 | 49.75 | | | 3.75 | 0.350012 | 3.218876 | 48.99427 |
| 26 | 50 | 48 | 49.5 | | | 3.5 | 0.397485 | 3.258097 | 48.61834 |
| 27 | 50 | 48 | 49.25 | | | 3.25 | 0.446085 | 3.295837 | 48.27759 |
| 28 | 49 | 47 | 47.75 | | | 1.75 | 0.779886 | 3.332205 | 47.97078 |
| 29 | 49 | 48 | 47.5 | | | 1.5 | 0.848172 | 3.367296 | 47.69636 |
| 30 | 48.5 | 47 | 47.25 | | | 1.25 | 0.923344 | 3.401197 | 47.45249 |
| 31 | 49 | 47 | 47.25 | | | 1.25 | 0.923344 | 3.433987 | 47.23715 |
| 32 | 49 | 46.5 | 47 | | | 1 | 1.008264 | 3.465736 | 47.04821 |
| 33 | 48.5 | 46 | 46.75 | | | 0.75 | 1.108075 | 3.496508 | 46.88346 |
| 34 | 48 | 47 | 47 | | | 1 | 1.008264 | 3.526361 | 46.7407 |
| 35 | 48 | 46 | 46.5 | | | 0.5 | 1.233722 | 3.555348 | 46.61775 |
| 36 | 48 | 47 | 46 | | | 0 | | 3.583519 | 46.5125 |
| 37 | 48 | 46 | 46 | | | 0 | | 3.610918 | 46.42296 |
| 38 | 48 | 46 | 46 | | | 0 | | 3.637586 | 46.34723 |
| 39 | 47.5 | 45 | 46 | | | 0 | | 3.663562 | 46.28356 |
| 40 | 48 | 46 | 46 | | | 0 | | 3.688879 | 46.23035 |

Table 5 Hardness values for A356 1 hr delay

| distance | hardness | | | | | | fit |
|---|---|---|---|---|---|---|---|
| 0 | 116 | | | H(x)-H min | ln I | ln X | 116 |
| 1 | 114.7 | H max | 116 | 13.9 | -2.38806 | 0 | 114.9866 |
| 2 | 114.2 | H min | 100.8 | 13.4 | -2.05158 | 0.693147 | 114.0407 |
| 3 | 109.4 | | | 8.6 | -0.55954 | 1.098612 | 113.1579 |
| 4 | 110.0 | del H | 15.2 | 9.2 | -0.68177 | 1.386294 | 112.334 |
| 5 | 109.9 | | | 9.1 | -0.65676 | 1.609438 | 111.5649 |
| 6 | 106.5 | k | 0.075 | 5.7 | -0.01339 | 1.791759 | 110.8472 |
| 7 | 103.7 | n | 0.92 | 2.9 | 0.504758 | 1.94591 | 110.1773 |
| 8 | 102.6 | | | 1.8 | 0.757768 | 2.079442 | 109.5521 |
| 9 | 105.5 | K1 | 0.995 | 4.7 | 0.160189 | 2.197225 | 108.9686 |
| 10 | 106.0 | | -0.00501 | 5.2 | 0.07012 | 2.302585 | 108.424 |
| 11 | 105.8 | | | 5.0 | 0.100038 | 2.397895 | 107.9156 |
| 12 | 108.6 | | | 7.8 | -0.39511 | 2.484907 | 107.4412 |
| 13 | 103.9 | | | 3.1 | 0.460289 | 2.564949 | 106.9984 |
| 14 | 106.8 | | | 6.0 | -0.07905 | 2.639057 | 106.5852 |
| 15 | 106.3 | | | 5.5 | 0.019393 | 2.70805 | 106.1994 |
| 16 | 104.7 | | | 3.9 | 0.31716 | 2.772589 | 105.8394 |
| 17 | 103.8 | | | 3.0 | 0.487508 | 2.833213 | 105.5034 |
| 18 | 103.3 | | | 2.5 | 0.583198 | 2.890372 | 105.1899 |
| 19 | 105.2 | | | 4.4 | 0.224039 | 2.944439 | 104.8972 |
| 20 | 104.3 | | | 3.5 | 0.377788 | 2.995732 | 104.624 |
| 21 | 104.6 | | | 3.8 | 0.336143 | 3.044522 | 104.369 |
| 22 | 102.3 | | | 1.5 | 0.834985 | 3.091042 | 104.1311 |
| 23 | 105.0 | | | 4.2 | 0.251701 | 3.135494 | 103.909 |
| 24 | 104.6 | | | 3.8 | 0.326634 | 3.178054 | 103.7017 |
| 25 | 101.2 | | | 0.4 | 1.280035 | 3.218876 | 103.5082 |
| 26 | 104.2 | | | 3.4 | 0.397274 | 3.258097 | 103.3277 |
| 27 | 103.2 | | | 2.4 | 0.609171 | 3.295837 | 103.1591 |
| 28 | 104.5 | | | 3.7 | 0.345689 | 3.332205 | 103.0018 |
| 29 | 104.5 | | | 3.7 | 0.352073 | 3.367296 | 102.855 |
| 30 | 103.0 | | | 2.2 | 0.655077 | 3.401197 | 102.718 |
| 31 | 105.7 | | | 4.9 | 0.130051 | 3.433987 | 102.5901 |
| 32 | 105.2 | | | 4.4 | 0.224039 | 3.465736 | 102.4708 |
| 33 | 102.5 | | | 1.7 | 0.788693 | 3.496508 | 102.3594 |
| 34 | 103.5 | | | 2.7 | 0.554153 | 3.526361 | 102.2554 |
| 35 | 100.8 | | | 0.0 | #NUM! | 3.555348 | 102.1584 |
| 36 | 102.6 | | | 1.8 | 0.762119 | 3.583519 | 102.0678 |
| 37 | 102.6 | | | 1.8 | 0.753439 | 3.610918 | 101.9833 |
| 38 | 101.8 | | | 1.0 | 0.988986 | 3.637586 | 101.9044 |
| 39 | 103.5 | | | 2.7 | 0.554153 | 3.663562 | 101.8308 |
| 40 | 102.7 | | | 1.9 | 0.736327 | 3.688879 | 101.762 |

Table 6 Hardness values for A356 120 hr delay

| distance | | | | | | | fit |
|---|---|---|---|---|---|---|---|
| 0 | 119 | | | H(x)-H min | ln I | ln X | 119 |
| 1 | 117.7 | H max | 119 | 13.9 | -1.3022 | 0 | 117.7865 |
| 2 | 117.2 | H min | 100.8 | 13.4 | -1.17552 | 0.693147 | 116.654 |
| 3 | 112.4 | | | 8.6 | -0.28555 | 1.098612 | 115.597 |
| 4 | 113.0 | del H | 18.2 | 9.2 | -0.3771 | 1.386294 | 114.6104 |
| 5 | 112.9 | | | 9.1 | -0.3586 | 1.609438 | 113.6896 |
| 6 | 109.5 | k | 0.075 | 5.7 | 0.154283 | 1.791759 | 112.8302 |
| 7 | 106.7 | n | 0.92 | 2.9 | 0.607976 | 1.94591 | 112.0281 |
| 8 | 105.6 | | | 1.8 | 0.83882 | 2.079442 | 111.2795 |
| 9 | 108.5 | k | 0.995 | 4.7 | 0.302959 | 2.197225 | 110.5808 |
| 10 | 109.0 | | -0.00501 | 5.2 | 0.225351 | 2.302585 | 109.9287 |
| 11 | 108.8 | | | 5.0 | 0.251023 | 2.397895 | 109.32 |
| 12 | 111.6 | | | 7.8 | -0.15814 | 2.484907 | 108.752 |
| 13 | 106.9 | | | 3.1 | 0.567957 | 2.564949 | 108.2218 |
| 14 | 109.8 | | | 6.0 | 0.09905 | 2.639057 | 107.727 |
| 15 | 109.3 | | | 5.5 | 0.182079 | 2.70805 | 107.2651 |
| 16 | 107.7 | | | 3.9 | 0.440413 | 2.772589 | 106.8341 |
| 17 | 106.8 | | | 3.0 | 0.592432 | 2.833213 | 106.4318 |
| 18 | 106.3 | | | 2.5 | 0.67899 | 2.890372 | 106.0563 |
| 19 | 108.2 | | | 4.4 | 0.358545 | 2.944439 | 105.7058 |
| 20 | 107.3 | | | 3.5 | 0.494196 | 2.995732 | 105.3787 |
| 21 | 107.6 | | | 3.8 | 0.457213 | 3.044522 | 105.0735 |
| 22 | 105.3 | | | 1.5 | 0.910235 | 3.091042 | 104.7885 |
| 23 | 108.0 | | | 4.2 | 0.382768 | 3.135494 | 104.5226 |
| 24 | 107.6 | | | 3.8 | 0.448793 | 3.178054 | 104.2744 |
| 25 | 104.2 | | | 0.4 | 1.328901 | 3.218876 | 104.0427 |
| 26 | 107.2 | | | 3.4 | 0.511559 | 3.258097 | 103.8265 |
| 27 | 106.2 | | | 2.4 | 0.702618 | 3.295837 | 103.6248 |
| 28 | 107.5 | | | 3.7 | 0.465675 | 3.332205 | 103.4364 |
| 29 | 107.5 | | | 3.7 | 0.471339 | 3.367296 | 103.2606 |
| 30 | 106.0 | | | 2.2 | 0.744514 | 3.401197 | 103.0966 |
| 31 | 108.7 | | | 4.9 | 0.276883 | 3.433987 | 102.9435 |
| 32 | 108.2 | | | 4.4 | 0.358545 | 3.465736 | 102.8005 |
| 33 | 105.5 | | | 1.7 | 0.867372 | 3.496508 | 102.6672 |
| 34 | 106.5 | | | 2.7 | 0.652634 | 3.526361 | 102.5427 |
| 35 | 103.8 | | | 0.0 | #NUM! | 3.555348 | 102.4265 |
| 36 | 105.6 | | | 1.8 | 0.842832 | 3.583519 | 102.318 |
| 37 | 105.6 | | | 1.8 | 0.834828 | 3.610918 | 102.2168 |
| 38 | 104.8 | | | 1.0 | 1.053835 | 3.637586 | 102.1224 |
| 39 | 106.5 | | | 2.7 | 0.652634 | 3.663562 | 102.0342 |
| 40 | 105.7 | | | 1.9 | 0.819065 | 3.688879 | 101.9519 |

Table 7 Hardness values for B319 1hr delay

| Distance | Hardness | | | H(x)-H min | ln(G) | | Avrami | x (mm) | ln x |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 139.0 | H max | 139 | 24 | | | 139 | 0.0 | |
| 1 | 137.0 | H min | 115 | 22 | -2.44172 | 0 | 136.9237 | 1.6 | 0.46216 |
| 2 | 136.5 | del H | 24 | 21.5 | -2.20727 | 0.693147 | 135.0269 | 3.2 | 1.155308 |
| 3 | 135.0 | | | 20.01667 | -1.70656 | 1.098612 | 133.2943 | 4.8 | 1.560773 |
| 4 | 133.0 | k | 0.057 | 18 | -1.2459 | 1.386294 | 131.7116 | 6.4 | 1.848455 |
| 5 | 132.0 | n | 1 | 17 | -1.06467 | 1.609438 | 130.2658 | 7.9 | 2.071598 |
| 6 | 131.5 | | | 16.5 | -0.98165 | 1.791759 | 128.9451 | 9.5 | 2.25392 |
| 7 | 131.0 | | | 16 | -0.90272 | 1.94591 | 127.7387 | 11.1 | 2.408071 |
| 8 | 128.8 | | | 13.8 | -0.5917 | 2.079442 | 126.6366 | 12.7 | 2.541602 |
| 9 | 128.6 | | | 13.6 | -0.56566 | 2.197225 | 125.6299 | 14.3 | 2.659385 |
| 10 | 128.2 | | | 13.16667 | -0.51022 | 2.302585 | 124.7102 | 15.9 | 2.764746 |
| 11 | 127.6 | | | 12.6 | -0.4395 | 2.397895 | 123.8701 | 17.5 | 2.860056 |
| 12 | 126.0 | | | 11 | -0.24826 | 2.484907 | 123.1028 | 19.1 | 2.947067 |
| 13 | 127.3 | | | 12.33333 | -0.40684 | 2.564949 | 122.4017 | 20.6 | 3.02711 |
| 14 | 128.3 | | | 13.33333 | -0.53139 | 2.639057 | 121.7614 | 22.2 | 3.101218 |
| 15 | 127.2 | | | 12.16667 | -0.38661 | 2.70805 | 121.1764 | 23.8 | 3.170211 |
| 16 | 127.2 | | | 12.16667 | -0.38661 | 2.772589 | 120.6421 | 25.4 | 3.234749 |
| 17 | 124.7 | | | 9.666667 | -0.095 | 2.833213 | 120.154 | 27.0 | 3.295374 |
| 18 | 125.0 | | | 10 | -0.133 | 2.890372 | 119.7081 | 28.6 | 3.352532 |
| 19 | 124.8 | | | 9.833333 | -0.11398 | 2.944439 | 119.3008 | 30.2 | 3.406599 |
| 20 | 124.3 | | | 9.333333 | -0.05714 | 2.995732 | 118.9287 | 31.8 | 3.457893 |
| 21 | 126.0 | | | 11 | -0.24826 | 3.044522 | 118.5888 | 33.3 | 3.506683 |
| 22 | 122.0 | | | 7 | 0.208755 | 3.091042 | 118.2783 | 34.9 | 3.553203 |
| 23 | 121.5 | | | 6.5 | 0.267162 | 3.135494 | 117.9947 | 36.5 | 3.597655 |
| 24 | 123.7 | | | 8.666667 | 0.018399 | 3.178054 | 117.7356 | 38.1 | 3.640214 |
| 25 | 123.7 | | | 8.666667 | 0.018399 | 3.218876 | 117.4989 | 39.7 | 3.681036 |
| 26 | 120.7 | | | 5.666667 | 0.367038 | 3.258097 | 117.2827 | 41.3 | 3.720257 |
| 27 | 120.0 | | | 5 | 0.450194 | 3.295837 | 117.0853 | 42.9 | 3.757997 |
| 28 | 117.7 | | | 2.666667 | 0.787195 | 3.332205 | 116.9049 | 44.5 | 3.794365 |
| 29 | 121.8 | | | 6.833333 | 0.228124 | 3.367296 | 116.7401 | 46.0 | 3.829456 |
| 30 | 119.0 | | | 4 | 0.583198 | 3.401197 | 116.5895 | 47.6 | 3.863358 |
| 31 | 120.5 | | | 5.5 | 0.387509 | 3.433987 | 116.452 | 49.2 | 3.896148 |
| 32 | 119.3 | | | 4.333333 | 0.537497 | 3.465736 | 116.3264 | 50.8 | 3.927896 |
| 33 | 119.7 | | | 4.666667 | 0.493237 | 3.496508 | 116.2116 | 52.4 | 3.958668 |
| 34 | 119.3 | | | 4.333333 | 0.537497 | 3.526361 | 116.1068 | 54.0 | 3.988521 |
| 35 | 116.7 | | | 1.666667 | 0.98104 | 3.555348 | 116.0111 | 55.6 | 4.017509 |
| 36 | 115.7 | | | 0.666667 | 1.276345 | 3.583519 | 115.9236 | 57.2 | 4.045679 |
| 37 | 116.3 | | | 1.333333 | 1.061385 | 3.610918 | 115.8437 | 58.7 | 4.073078 |
| 38 | 116.8 | | | 1.833333 | 0.944652 | 3.637586 | 115.7707 | 60.3 | 4.099747 |
| 39 | 115.5 | | | 0.5 | 1.353565 | 3.663562 | 115.704 | 61.9 | 4.125722 |
| 40 | 115.0 | | | 0 | | | 115.6431 | 63.5 | 4.15104 |

Table 8 Hardness values for B319 120hr delay

| Distance | Hardness | | | H(x)-Hmin | ln(H) | ln X | Avrami |
|---|---|---|---|---|---|---|---|
| 0 | 141.5 | H max | 141.5 | 24 | #NUM! | #NUM! | 141.5 |
| 1 | 140.1667 | H min | 117.5 | 22.66667 | -2.86193 | 0 | 140.1703 |
| 2 | 140.1667 | del H | 24 | 22.66667 | -2.86193 | 0.693147 | 138.9142 |
| 3 | 137.5167 | | | 20.01667 | -1.70656 | 1.098612 | 137.7277 |
| 4 | 133 | | | 15.5 | -0.82733 | 1.386294 | 136.607 |
| 5 | 134 | k | 0.057 | 16.5 | -0.98165 | 1.609438 | 135.5483 |
| 6 | 133.5 | n | 1 | 16 | -0.90272 | 1.791759 | 134.5484 |
| 7 | 133.5 | | | 16 | -0.90272 | 1.94591 | 133.6038 |
| 8 | 131.1667 | | | 13.66667 | -0.57431 | 2.079442 | 132.7115 |
| 9 | 131.3333 | | | 13.83333 | -0.59607 | 2.197225 | 131.8687 |
| 10 | 130.6667 | | | 13.16667 | -0.51022 | 2.302585 | 131.0726 |
| 11 | 131.1667 | | | 13.66667 | -0.57431 | 2.397895 | 130.3206 |
| 12 | 128.5 | | | 11 | -0.24826 | 2.484907 | 129.6103 |
| 13 | 129.8333 | | | 12.33333 | -0.40684 | 2.564949 | 128.9393 |
| 14 | 130.8333 | | | 13.33333 | -0.53139 | 2.639057 | 128.3055 |
| 15 | 129.6667 | | | 12.16667 | -0.38661 | 2.70805 | 127.7068 |
| 16 | 129.6667 | | | 12.16667 | -0.38661 | 2.772589 | 127.1413 |
| 17 | 127.1667 | | | 9.666667 | -0.095 | 2.833213 | 126.6071 |
| 18 | 127.5 | | | 10 | -0.133 | 2.890372 | 126.1025 |
| 19 | 127.3333 | | | 9.833333 | -0.11398 | 2.944439 | 125.6259 |
| 20 | 126.8333 | | | 9.333333 | -0.05714 | 2.995732 | 125.1757 |
| 21 | 128.5 | | | 11 | -0.24826 | 3.044522 | 124.7504 |
| 22 | 124.5 | | | 7 | 0.208755 | 3.091042 | 124.3487 |
| 23 | 124 | | | 6.5 | 0.267162 | 3.135494 | 123.9692 |
| 24 | 126.1667 | | | 8.666667 | 0.018399 | 3.178054 | 123.6108 |
| 25 | 126.1667 | | | 8.666667 | 0.018399 | 3.218876 | 123.2722 |
| 26 | 123.1667 | | | 5.666667 | 0.367038 | 3.258097 | 122.9524 |
| 27 | 122.5 | | | 5 | 0.450194 | 3.295837 | 122.6503 |
| 28 | 120.1667 | | | 2.666667 | 0.787195 | 3.332205 | 122.3649 |
| 29 | 124.3333 | | | 6.833333 | 0.228124 | 3.367296 | 122.0954 |
| 30 | 121.5 | | | 4 | 0.583198 | 3.401197 | 121.8408 |
| 31 | 123 | | | 5.5 | 0.387509 | 3.433987 | 121.6003 |
| 32 | 121.8333 | | | 4.333333 | 0.537497 | 3.465736 | 121.3731 |
| 33 | 122.1667 | | | 4.666667 | 0.493237 | 3.496508 | 121.1585 |
| 34 | 121.8333 | | | 4.333333 | 0.537497 | 3.526361 | 120.9558 |
| 35 | 119.1667 | | | 1.666667 | 0.98104 | 3.555348 | 120.7643 |
| 36 | 118.1667 | | | 0.666667 | 1.276345 | 3.583519 | 120.5835 |
| 37 | 118.8333 | | | 1.333333 | 1.061385 | 3.610918 | 120.4126 |
| 38 | 119.3333 | | | 1.833333 | 0.944652 | 3.637586 | 120.2512 |
| 39 | 118 | | | 0.5 | 1.353565 | 3.663562 | 120.0988 |
| 40 | 117.5 | | | 0 | | | 119.9548 |

# APPENDIX B

# TENSILE DATA

Table 9 UTS values for 7075 1 hr delay

| x (1/16") | strength | x (mm) |
|---|---|---|
| 0 | 362.8 | 0 |
| 1 | 362.4794 | 1.5875 |
| 2 | 361.5216 | 3.175 |
| 3 | 359.9377 | 4.7625 |
| 4 | 357.7464 | 6.35 |
| 5 | 354.9731 | 7.9375 |
| 6 | 351.6499 | 9.525 |
| 7 | 347.8145 | 11.1125 |
| 8 | 343.5096 | 12.7 |
| 9 | 338.7826 | 14.2875 |
| 10 | 333.684 | 15.875 |
| 11 | 328.267 | 17.4625 |
| 12 | 322.5863 | 19.05 |
| 13 | 316.6975 | 20.6375 |
| 14 | 310.656 | 22.225 |
| 15 | 304.5161 | 23.8125 |
| 16 | 298.3304 | 25.4 |
| 17 | 292.1489 | 26.9875 |
| 18 | 286.0186 | 28.575 |
| 19 | 279.9828 | 30.1625 |
| 20 | 274.0807 | 31.75 |
| 21 | 268.3474 | 33.3375 |
| 22 | 262.813 | 34.925 |
| 23 | 257.5034 | 36.5125 |
| 24 | 252.4394 | 38.1 |
| 25 | 247.6374 | 39.6875 |
| 26 | 243.1094 | 41.275 |
| 27 | 238.8632 | 42.8625 |
| 28 | 234.9026 | 44.45 |
| 29 | 231.2277 | 46.0375 |
| 30 | 227.8356 | 47.625 |
| 31 | 224.7204 | 49.2125 |
| 32 | 221.874 | 50.8 |
| 33 | 219.2859 | 52.3875 |
| 34 | 216.9442 | 53.975 |
| 35 | 214.8357 | 55.5625 |
| 36 | 212.9463 | 57.15 |
| 37 | 211.2611 | 58.7375 |
| 38 | 209.7652 | 60.325 |
| 39 | 208.4435 | 61.9125 |
| 40 | 207.2811 | 63.5 |

Table 10 YS values for 7075 1hr delay

| x(1/16") | Strength | x(1/16") |
|---|---|---|
| 0 | 353.3 | 0 |
| 1 | 352.9777 | 1.5875 |
| 2 | 352.0145 | 3.175 |
| 3 | 350.4218 | 4.7625 |
| 4 | 348.2184 | 6.35 |
| 5 | 345.4298 | 7.9375 |
| 6 | 342.0881 | 9.525 |
| 7 | 338.2314 | 11.1125 |
| 8 | 333.9027 | 12.7 |
| 9 | 329.1495 | 14.2875 |
| 10 | 324.0226 | 15.875 |
| 11 | 318.5756 | 17.4625 |
| 12 | 312.8634 | 19.05 |
| 13 | 306.942 | 20.6375 |
| 14 | 300.867 | 22.225 |
| 15 | 294.6931 | 23.8125 |
| 16 | 288.4731 | 25.4 |
| 17 | 282.2574 | 26.9875 |
| 18 | 276.0931 | 28.575 |
| 19 | 270.0238 | 30.1625 |
| 20 | 264.0891 | 31.75 |
| 21 | 258.3239 | 33.3375 |
| 22 | 252.7589 | 34.925 |
| 23 | 247.4198 | 36.5125 |
| 24 | 242.3277 | 38.1 |
| 25 | 237.4992 | 39.6875 |
| 26 | 232.9461 | 41.275 |
| 27 | 228.6764 | 42.8625 |
| 28 | 224.6938 | 44.45 |
| 29 | 220.9985 | 46.0375 |
| 30 | 217.5876 | 47.625 |
| 31 | 214.4552 | 49.2125 |
| 32 | 211.593 | 50.8 |
| 33 | 208.9905 | 52.3875 |
| 34 | 206.6359 | 53.975 |
| 35 | 204.5157 | 55.5625 |
| 36 | 202.6158 | 57.15 |
| 37 | 200.9213 | 58.7375 |
| 38 | 199.4171 | 60.325 |
| 39 | 198.0881 | 61.9125 |
| 40 | 196.9192 | 63.5 |

Table 11 UTS values for 7075 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 390.7 | 0 |
| 1 | 390.4081 | 1.5875 |
| 2 | 389.5357 | 3.175 |
| 3 | 388.0933 | 4.7625 |
| 4 | 386.0976 | 6.35 |
| 5 | 383.572 | 7.9375 |
| 6 | 380.5455 | 9.525 |
| 7 | 377.0525 | 11.1125 |
| 8 | 373.132 | 12.7 |
| 9 | 368.827 | 14.2875 |
| 10 | 364.1836 | 15.875 |
| 11 | 359.2503 | 17.4625 |
| 12 | 354.0768 | 19.05 |
| 13 | 348.7138 | 20.6375 |
| 14 | 343.2117 | 22.225 |
| 15 | 337.62 | 23.8125 |
| 16 | 331.9866 | 25.4 |
| 17 | 326.357 | 26.9875 |
| 18 | 320.7741 | 28.575 |
| 19 | 315.2772 | 30.1625 |
| 20 | 309.9021 | 31.75 |
| 21 | 304.6806 | 33.3375 |
| 22 | 299.6404 | 34.925 |
| 23 | 294.8048 | 36.5125 |
| 24 | 290.193 | 38.1 |
| 25 | 285.8198 | 39.6875 |
| 26 | 281.6961 | 41.275 |
| 27 | 277.829 | 42.8625 |
| 28 | 274.222 | 44.45 |
| 29 | 270.8752 | 46.0375 |
| 30 | 267.786 | 47.625 |
| 31 | 264.949 | 49.2125 |
| 32 | 262.3566 | 50.8 |
| 33 | 259.9996 | 52.3875 |
| 34 | 257.867 | 53.975 |
| 35 | 255.9468 | 55.5625 |
| 36 | 254.2261 | 57.15 |
| 37 | 252.6914 | 58.7375 |
| 38 | 251.329 | 60.325 |
| 39 | 250.1253 | 61.9125 |
| 40 | 249.0667 | 63.5 |

Table 12 YS values for 7075 120 hr delay

| x(1/16") | Strength | x(mm) |
|---|---|---|
| 0 | 378.3 | 0 |
| 1 | 378.0039 | 1.5875 |
| 2 | 377.1192 | 3.175 |
| 3 | 375.6562 | 4.7625 |
| 4 | 373.6322 | 6.35 |
| 5 | 371.0708 | 7.9375 |
| 6 | 368.0013 | 9.525 |
| 7 | 364.4587 | 11.1125 |
| 8 | 360.4826 | 12.7 |
| 9 | 356.1165 | 14.2875 |
| 10 | 351.4071 | 15.875 |
| 11 | 346.4037 | 17.4625 |
| 12 | 341.1568 | 19.05 |
| 13 | 335.7177 | 20.6375 |
| 14 | 330.1375 | 22.225 |
| 15 | 324.4664 | 23.8125 |
| 16 | 318.753 | 25.4 |
| 17 | 313.0434 | 26.9875 |
| 18 | 307.3812 | 28.575 |
| 19 | 301.8063 | 30.1625 |
| 20 | 296.3549 | 31.75 |
| 21 | 291.0593 | 33.3375 |
| 22 | 285.9475 | 34.925 |
| 23 | 281.0432 | 36.5125 |
| 24 | 276.3659 | 38.1 |
| 25 | 271.9306 | 39.6875 |
| 26 | 267.7484 | 41.275 |
| 27 | 263.8264 | 42.8625 |
| 28 | 260.1681 | 44.45 |
| 29 | 256.7738 | 46.0375 |
| 30 | 253.6407 | 47.625 |
| 31 | 250.7634 | 49.2125 |
| 32 | 248.1343 | 50.8 |
| 33 | 245.7438 | 52.3875 |
| 34 | 243.581 | 53.975 |
| 35 | 241.6335 | 55.5625 |
| 36 | 239.8883 | 57.15 |
| 37 | 238.3318 | 58.7375 |
| 38 | 236.9501 | 60.325 |
| 39 | 235.7294 | 61.9125 |
| 40 | 234.6557 | 63.5 |

Table 13 UTS values for 6061 1hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 361.2 | 0 |
| 1 | 360.9266 | 1.5875 |
| 2 | 360.1102 | 3.175 |
| 3 | 358.7619 | 4.7625 |
| 4 | 356.9003 | 6.35 |
| 5 | 354.5505 | 7.9375 |
| 6 | 351.7438 | 9.525 |
| 7 | 348.5173 | 11.1125 |
| 8 | 344.9126 | 12.7 |
| 9 | 340.975 | 14.2875 |
| 10 | 336.7528 | 15.875 |
| 11 | 332.2964 | 17.4625 |
| 12 | 327.6566 | 19.05 |
| 13 | 322.8846 | 20.6375 |
| 14 | 318.0303 | 22.225 |
| 15 | 313.1421 | 23.8125 |
| 16 | 308.2657 | 25.4 |
| 17 | 303.4434 | 26.9875 |
| 18 | 298.7141 | 28.575 |
| 19 | 294.1124 | 30.1625 |
| 20 | 289.6684 | 31.75 |
| 21 | 285.4076 | 33.3375 |
| 22 | 281.351 | 34.925 |
| 23 | 277.5149 | 36.5125 |
| 24 | 273.911 | 38.1 |
| 25 | 270.547 | 39.6875 |
| 26 | 267.4266 | 41.275 |
| 27 | 264.5497 | 42.8625 |
| 28 | 261.9135 | 44.45 |
| 29 | 259.512 | 46.0375 |
| 30 | 257.337 | 47.625 |
| 31 | 255.3785 | 49.2125 |
| 32 | 253.625 | 50.8 |
| 33 | 252.0638 | 52.3875 |
| 34 | 250.6814 | 53.975 |
| 35 | 249.4642 | 55.5625 |
| 36 | 248.3982 | 57.15 |
| 37 | 247.4696 | 58.7375 |
| 38 | 246.6651 | 60.325 |
| 39 | 245.9718 | 61.9125 |
| 40 | 245.3774 | 63.5 |

Table 14 YS values for 6061 1 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 341.5 | 0 |
| 1 | 341.2289 | 1.5875 |
| 2 | 340.4193 | 3.175 |
| 3 | 339.0825 | 4.7625 |
| 4 | 337.2365 | 6.35 |
| 5 | 334.9064 | 7.9375 |
| 6 | 332.1234 | 9.525 |
| 7 | 328.9241 | 11.1125 |
| 8 | 325.3497 | 12.7 |
| 9 | 321.4452 | 14.2875 |
| 10 | 317.2586 | 15.875 |
| 11 | 312.8397 | 17.4625 |
| 12 | 308.2389 | 19.05 |
| 13 | 303.5071 | 20.6375 |
| 14 | 298.6937 | 22.225 |
| 15 | 293.8467 | 23.8125 |
| 16 | 289.0112 | 25.4 |
| 17 | 284.2296 | 26.9875 |
| 18 | 279.5401 | 28.575 |
| 19 | 274.9771 | 30.1625 |
| 20 | 270.5705 | 31.75 |
| 21 | 266.3456 | 33.3375 |
| 22 | 262.3232 | 34.925 |
| 23 | 258.5193 | 36.5125 |
| 24 | 254.9458 | 38.1 |
| 25 | 251.6101 | 39.6875 |
| 26 | 248.5159 | 41.275 |
| 27 | 245.6633 | 42.8625 |
| 28 | 243.0492 | 44.45 |
| 29 | 240.6679 | 46.0375 |
| 30 | 238.5113 | 47.625 |
| 31 | 236.5693 | 49.2125 |
| 32 | 234.8305 | 50.8 |
| 33 | 233.2824 | 52.3875 |
| 34 | 231.9117 | 53.975 |
| 35 | 230.7047 | 55.5625 |
| 36 | 229.6477 | 57.15 |
| 37 | 228.7269 | 58.7375 |
| 38 | 227.9292 | 60.325 |
| 39 | 227.2417 | 61.9125 |
| 40 | 226.6523 | 63.5 |

Table 15 UTS values for 6061 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 327.1 | 0 |
| 1 | 326.9994 | 1.5875 |
| 2 | 326.6991 | 3.175 |
| 3 | 326.2032 | 4.7625 |
| 4 | 325.5184 | 6.35 |
| 5 | 324.654 | 7.9375 |
| 6 | 323.6216 | 9.525 |
| 7 | 322.4347 | 11.1125 |
| 8 | 321.1087 | 12.7 |
| 9 | 319.6603 | 14.2875 |
| 10 | 318.1072 | 15.875 |
| 11 | 316.4679 | 17.4625 |
| 12 | 314.7612 | 19.05 |
| 13 | 313.0059 | 20.6375 |
| 14 | 311.2202 | 22.225 |
| 15 | 309.4222 | 23.8125 |
| 16 | 307.6284 | 25.4 |
| 17 | 305.8545 | 26.9875 |
| 18 | 304.1149 | 28.575 |
| 19 | 302.4222 | 30.1625 |
| 20 | 300.7874 | 31.75 |
| 21 | 299.2201 | 33.3375 |
| 22 | 297.7279 | 34.925 |
| 23 | 296.3168 | 36.5125 |
| 24 | 294.9912 | 38.1 |
| 25 | 293.7537 | 39.6875 |
| 26 | 292.6059 | 41.275 |
| 27 | 291.5477 | 42.8625 |
| 28 | 290.5779 | 44.45 |
| 29 | 289.6945 | 46.0375 |
| 30 | 288.8945 | 47.625 |
| 31 | 288.1741 | 49.2125 |
| 32 | 287.5291 | 50.8 |
| 33 | 286.9548 | 52.3875 |
| 34 | 286.4463 | 53.975 |
| 35 | 285.9985 | 55.5625 |
| 36 | 285.6064 | 57.15 |
| 37 | 285.2648 | 58.7375 |
| 38 | 284.9689 | 60.325 |
| 39 | 284.7139 | 61.9125 |
| 40 | 284.4952 | 63.5 |

Table 16 YS values for 6061 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 318.5 | 0 |
| 1 | 318.3565 | 1.5875 |
| 2 | 317.9278 | 3.175 |
| 3 | 317.22 | 4.7625 |
| 4 | 316.2427 | 6.35 |
| 5 | 315.009 | 7.9375 |
| 6 | 313.5355 | 9.525 |
| 7 | 311.8416 | 11.1125 |
| 8 | 309.9491 | 12.7 |
| 9 | 307.8819 | 14.2875 |
| 10 | 305.6652 | 15.875 |
| 11 | 303.3256 | 17.4625 |
| 12 | 300.8897 | 19.05 |
| 13 | 298.3844 | 20.6375 |
| 14 | 295.8359 | 22.225 |
| 15 | 293.2696 | 23.8125 |
| 16 | 290.7095 | 25.4 |
| 17 | 288.1778 | 26.9875 |
| 18 | 285.6949 | 28.575 |
| 19 | 283.279 | 30.1625 |
| 20 | 280.9459 | 31.75 |
| 21 | 278.709 | 33.3375 |
| 22 | 276.5793 | 34.925 |
| 23 | 274.5653 | 36.5125 |
| 24 | 272.6733 | 38.1 |
| 25 | 270.9072 | 39.6875 |
| 26 | 269.2689 | 41.275 |
| 27 | 267.7586 | 42.8625 |
| 28 | 266.3746 | 44.45 |
| 29 | 265.1138 | 46.0375 |
| 30 | 263.9719 | 47.625 |
| 31 | 262.9437 | 49.2125 |
| 32 | 262.0231 | 50.8 |
| 33 | 261.2035 | 52.3875 |
| 34 | 260.4778 | 53.975 |
| 35 | 259.8387 | 55.5625 |
| 36 | 259.279 | 57.15 |
| 37 | 258.7915 | 58.7375 |
| 38 | 258.3692 | 60.325 |
| 39 | 258.0052 | 61.9125 |
| 40 | 257.6931 | 63.5 |

Table 17 UTS values for A356 1 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 350 | 0 |
| 1 | 346.6663 | 1.5875 |
| 2 | 343.5549 | 3.175 |
| 3 | 340.651 | 4.7625 |
| 4 | 337.9406 | 6.35 |
| 5 | 335.411 | 7.9375 |
| 6 | 333.05 | 9.525 |
| 7 | 330.8465 | 11.1125 |
| 8 | 328.7899 | 12.7 |
| 9 | 326.8703 | 14.2875 |
| 10 | 325.0788 | 15.875 |
| 11 | 323.4067 | 17.4625 |
| 12 | 321.8461 | 19.05 |
| 13 | 320.3896 | 20.6375 |
| 14 | 319.0301 | 22.225 |
| 15 | 317.7613 | 23.8125 |
| 16 | 316.5771 | 25.4 |
| 17 | 315.4719 | 26.9875 |
| 18 | 314.4403 | 28.575 |
| 19 | 313.4775 | 30.1625 |
| 20 | 312.5789 | 31.75 |
| 21 | 311.7402 | 33.3375 |
| 22 | 310.9575 | 34.925 |
| 23 | 310.2269 | 36.5125 |
| 24 | 309.5451 | 38.1 |
| 25 | 308.9087 | 39.6875 |
| 26 | 308.3147 | 41.275 |
| 27 | 307.7603 | 42.8625 |
| 28 | 307.2429 | 44.45 |
| 29 | 306.76 | 46.0375 |
| 30 | 306.3093 | 47.625 |
| 31 | 305.8886 | 49.2125 |
| 32 | 305.496 | 50.8 |
| 33 | 305.1296 | 52.3875 |
| 34 | 304.7876 | 53.975 |
| 35 | 304.4684 | 55.5625 |
| 36 | 304.1704 | 57.15 |
| 37 | 303.8924 | 58.7375 |
| 38 | 303.6329 | 60.325 |
| 39 | 303.3907 | 61.9125 |
| 40 | 303.1646 | 63.5 |

Table 18 YS values for A356 1hr delay

| x (mm) | Strength | x (mm) |
|---|---|---|
| 0 | 275 | 0 |
| 1 | 271.6663 | 1.5875 |
| 2 | 268.5549 | 3.175 |
| 3 | 265.651 | 4.7625 |
| 4 | 262.9406 | 6.35 |
| 5 | 260.411 | 7.9375 |
| 6 | 258.05 | 9.525 |
| 7 | 255.8465 | 11.1125 |
| 8 | 253.7899 | 12.7 |
| 9 | 251.8703 | 14.2875 |
| 10 | 250.0788 | 15.875 |
| 11 | 248.4067 | 17.4625 |
| 12 | 246.8461 | 19.05 |
| 13 | 245.3896 | 20.6375 |
| 14 | 244.0301 | 22.225 |
| 15 | 242.7613 | 23.8125 |
| 16 | 241.5771 | 25.4 |
| 17 | 240.4719 | 26.9875 |
| 18 | 239.4403 | 28.575 |
| 19 | 238.4775 | 30.1625 |
| 20 | 237.5789 | 31.75 |
| 21 | 236.7402 | 33.3375 |
| 22 | 235.9575 | 34.925 |
| 23 | 235.2269 | 36.5125 |
| 24 | 234.5451 | 38.1 |
| 25 | 233.9087 | 39.6875 |
| 26 | 233.3147 | 41.275 |
| 27 | 232.7603 | 42.8625 |
| 28 | 232.2429 | 44.45 |
| 29 | 231.76 | 46.0375 |
| 30 | 231.3093 | 47.625 |
| 31 | 230.8886 | 49.2125 |
| 32 | 230.496 | 50.8 |
| 33 | 230.1296 | 52.3875 |
| 34 | 229.7876 | 53.975 |
| 35 | 229.4684 | 55.5625 |
| 36 | 229.1704 | 57.15 |
| 37 | 228.8924 | 58.7375 |
| 38 | 228.6329 | 60.325 |
| 39 | 228.3907 | 61.9125 |
| 40 | 228.1646 | 63.5 |

Table 19 UTS values for A356 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 360 | 0 |
| 1 | 356.9997 | 1.5875 |
| 2 | 354.1994 | 3.175 |
| 3 | 351.5859 | 4.7625 |
| 4 | 349.1466 | 6.35 |
| 5 | 346.8699 | 7.9375 |
| 6 | 344.745 | 9.525 |
| 7 | 342.7618 | 11.1125 |
| 8 | 340.9109 | 12.7 |
| 9 | 339.1833 | 14.2875 |
| 10 | 337.5709 | 15.875 |
| 11 | 336.066 | 17.4625 |
| 12 | 334.6615 | 19.05 |
| 13 | 333.3506 | 20.6375 |
| 14 | 332.1271 | 22.225 |
| 15 | 330.9852 | 23.8125 |
| 16 | 329.9194 | 25.4 |
| 17 | 328.9247 | 26.9875 |
| 18 | 327.9963 | 28.575 |
| 19 | 327.1298 | 30.1625 |
| 20 | 326.321 | 31.75 |
| 21 | 325.5662 | 33.3375 |
| 22 | 324.8617 | 34.925 |
| 23 | 324.2042 | 36.5125 |
| 24 | 323.5905 | 38.1 |
| 25 | 323.0178 | 39.6875 |
| 26 | 322.4832 | 41.275 |
| 27 | 321.9843 | 42.8625 |
| 28 | 321.5186 | 44.45 |
| 29 | 321.084 | 46.0375 |
| 30 | 320.6784 | 47.625 |
| 31 | 320.2998 | 49.2125 |
| 32 | 319.9464 | 50.8 |
| 33 | 319.6166 | 52.3875 |
| 34 | 319.3088 | 53.975 |
| 35 | 319.0215 | 55.5625 |
| 36 | 318.7534 | 57.15 |
| 37 | 318.5031 | 58.7375 |
| 38 | 318.2696 | 60.325 |
| 39 | 318.0516 | 61.9125 |
| 40 | 317.8481 | 63.5 |

Table 20 YS values for A356 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 250 | 0 |
| 1 | 245.9996 | 1.5875 |
| 2 | 242.2659 | 3.175 |
| 3 | 238.7812 | 4.7625 |
| 4 | 235.5288 | 6.35 |
| 5 | 232.4932 | 7.9375 |
| 6 | 229.6601 | 9.525 |
| 7 | 227.0158 | 11.1125 |
| 8 | 224.5478 | 12.7 |
| 9 | 222.2444 | 14.2875 |
| 10 | 220.0946 | 15.875 |
| 11 | 218.0881 | 17.4625 |
| 12 | 216.2153 | 19.05 |
| 13 | 214.4675 | 20.6375 |
| 14 | 212.8361 | 22.225 |
| 15 | 211.3136 | 23.8125 |
| 16 | 209.8925 | 25.4 |
| 17 | 208.5662 | 26.9875 |
| 18 | 207.3284 | 28.575 |
| 19 | 206.173 | 30.1625 |
| 20 | 205.0947 | 31.75 |
| 21 | 204.0883 | 33.3375 |
| 22 | 203.149 | 34.925 |
| 23 | 202.2723 | 36.5125 |
| 24 | 201.4541 | 38.1 |
| 25 | 200.6904 | 39.6875 |
| 26 | 199.9776 | 41.275 |
| 27 | 199.3124 | 42.8625 |
| 28 | 198.6915 | 44.45 |
| 29 | 198.112 | 46.0375 |
| 30 | 197.5711 | 47.625 |
| 31 | 197.0664 | 49.2125 |
| 32 | 196.5952 | 50.8 |
| 33 | 196.1555 | 52.3875 |
| 34 | 195.7451 | 53.975 |
| 35 | 195.362 | 55.5625 |
| 36 | 195.0045 | 57.15 |
| 37 | 194.6709 | 58.7375 |
| 38 | 194.3594 | 60.325 |
| 39 | 194.0688 | 61.9125 |
| 40 | 193.7975 | 63.5 |

Table 21 UTS values for B319 1 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 385 | 0 |
| 1 | 380.2075 | 1.5875 |
| 2 | 375.6702 | 3.175 |
| 3 | 371.3746 | 4.7625 |
| 4 | 367.3076 | 6.35 |
| 5 | 363.4573 | 7.9375 |
| 6 | 359.8119 | 9.525 |
| 7 | 356.3607 | 11.1125 |
| 8 | 353.0933 | 12.7 |
| 9 | 349.9998 | 14.2875 |
| 10 | 347.0711 | 15.875 |
| 11 | 344.2983 | 17.4625 |
| 12 | 341.6732 | 19.05 |
| 13 | 339.1878 | 20.6375 |
| 14 | 336.8348 | 22.225 |
| 15 | 334.6072 | 23.8125 |
| 16 | 332.4981 | 25.4 |
| 17 | 330.5013 | 26.9875 |
| 18 | 328.6109 | 28.575 |
| 19 | 326.8211 | 30.1625 |
| 20 | 325.1266 | 31.75 |
| 21 | 323.5224 | 33.3375 |
| 22 | 322.0036 | 34.925 |
| 23 | 320.5657 | 36.5125 |
| 24 | 319.2043 | 38.1 |
| 25 | 317.9154 | 39.6875 |
| 26 | 316.6952 | 41.275 |
| 27 | 315.5399 | 42.8625 |
| 28 | 314.4462 | 44.45 |
| 29 | 313.4107 | 46.0375 |
| 30 | 312.4303 | 47.625 |
| 31 | 311.5021 | 49.2125 |
| 32 | 310.6234 | 50.8 |
| 33 | 309.7915 | 52.3875 |
| 34 | 309.0038 | 53.975 |
| 35 | 308.2581 | 55.5625 |
| 36 | 307.5521 | 57.15 |
| 37 | 306.8837 | 58.7375 |
| 38 | 306.2509 | 60.325 |
| 39 | 305.6518 | 61.9125 |
| 40 | 305.0846 | 63.5 |

Table 22 YS values for B319 1 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 315 | 0 |
| 1 | 310.4738 | 1.5875 |
| 2 | 306.1886 | 3.175 |
| 3 | 302.1315 | 4.7625 |
| 4 | 298.2905 | 6.35 |
| 5 | 294.6541 | 7.9375 |
| 6 | 291.2113 | 9.525 |
| 7 | 287.9518 | 11.1125 |
| 8 | 284.8659 | 12.7 |
| 9 | 281.9443 | 14.2875 |
| 10 | 279.1782 | 15.875 |
| 11 | 276.5595 | 17.4625 |
| 12 | 274.0802 | 19.05 |
| 13 | 271.733 | 20.6375 |
| 14 | 269.5107 | 22.225 |
| 15 | 267.4068 | 23.8125 |
| 16 | 265.4149 | 25.4 |
| 17 | 263.529 | 26.9875 |
| 18 | 261.7436 | 28.575 |
| 19 | 260.0533 | 30.1625 |
| 20 | 258.4529 | 31.75 |
| 21 | 256.9378 | 33.3375 |
| 22 | 255.5034 | 34.925 |
| 23 | 254.1453 | 36.5125 |
| 24 | 252.8596 | 38.1 |
| 25 | 251.6423 | 39.6875 |
| 26 | 250.4899 | 41.275 |
| 27 | 249.3988 | 42.8625 |
| 28 | 248.3658 | 44.45 |
| 29 | 247.3878 | 46.0375 |
| 30 | 246.4619 | 47.625 |
| 31 | 245.5853 | 49.2125 |
| 32 | 244.7554 | 50.8 |
| 33 | 243.9697 | 52.3875 |
| 34 | 243.2258 | 53.975 |
| 35 | 242.5216 | 55.5625 |
| 36 | 241.8548 | 57.15 |
| 37 | 241.2235 | 58.7375 |
| 38 | 240.6259 | 60.325 |
| 39 | 240.06 | 61.9125 |
| 40 | 239.5243 | 63.5 |

Table 23 UTS values for B319 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 395 | 0 |
| 1 | 391.0063 | 1.5875 |
| 2 | 387.2252 | 3.175 |
| 3 | 383.6455 | 4.7625 |
| 4 | 380.2564 | 6.35 |
| 5 | 377.0477 | 7.9375 |
| 6 | 374.0099 | 9.525 |
| 7 | 371.1339 | 11.1125 |
| 8 | 368.4111 | 12.7 |
| 9 | 365.8332 | 14.2875 |
| 10 | 363.3926 | 15.875 |
| 11 | 361.0819 | 17.4625 |
| 12 | 358.8943 | 19.05 |
| 13 | 356.8232 | 20.6375 |
| 14 | 354.8624 | 22.225 |
| 15 | 353.006 | 23.8125 |
| 16 | 351.2484 | 25.4 |
| 17 | 349.5844 | 26.9875 |
| 18 | 348.0091 | 28.575 |
| 19 | 346.5176 | 30.1625 |
| 20 | 345.1055 | 31.75 |
| 21 | 343.7687 | 33.3375 |
| 22 | 342.503 | 34.925 |
| 23 | 341.3047 | 36.5125 |
| 24 | 340.1702 | 38.1 |
| 25 | 339.0962 | 39.6875 |
| 26 | 338.0793 | 41.275 |
| 27 | 337.1166 | 42.8625 |
| 28 | 336.2051 | 44.45 |
| 29 | 335.3422 | 46.0375 |
| 30 | 334.5252 | 47.625 |
| 31 | 333.7518 | 49.2125 |
| 32 | 333.0195 | 50.8 |
| 33 | 332.3262 | 52.3875 |
| 34 | 331.6698 | 53.975 |
| 35 | 331.0484 | 55.5625 |
| 36 | 330.4601 | 57.15 |
| 37 | 329.9031 | 58.7375 |
| 38 | 329.3758 | 60.325 |
| 39 | 328.8765 | 61.9125 |
| 40 | 328.4038 | 63.5 |

Table 24 YS values for B319 120 hr delay

| x (1/16") | Strength | x (mm) |
|---|---|---|
| 0 | 330 | 0 |
| 1 | 324.6661 | 1.5875 |
| 2 | 319.6879 | 3.175 |
| 3 | 315.0416 | 4.7625 |
| 4 | 310.705 | 6.35 |
| 5 | 306.6576 | 7.9375 |
| 6 | 302.8801 | 9.525 |
| 7 | 299.3544 | 11.1125 |
| 8 | 296.0638 | 12.7 |
| 9 | 292.9925 | 14.2875 |
| 10 | 290.1261 | 15.875 |
| 11 | 287.4507 | 17.4625 |
| 12 | 284.9538 | 19.05 |
| 13 | 282.6233 | 20.6375 |
| 14 | 280.4482 | 22.225 |
| 15 | 278.4181 | 23.8125 |
| 16 | 276.5234 | 25.4 |
| 17 | 274.755 | 26.9875 |
| 18 | 273.1045 | 28.575 |
| 19 | 271.564 | 30.1625 |
| 20 | 270.1263 | 31.75 |
| 21 | 268.7844 | 33.3375 |
| 22 | 267.532 | 34.925 |
| 23 | 266.3631 | 36.5125 |
| 24 | 265.2721 | 38.1 |
| 25 | 264.2538 | 39.6875 |
| 26 | 263.3035 | 41.275 |
| 27 | 262.4165 | 42.8625 |
| 28 | 261.5887 | 44.45 |
| 29 | 260.816 | 46.0375 |
| 30 | 260.0949 | 47.625 |
| 31 | 259.4218 | 49.2125 |
| 32 | 258.7936 | 50.8 |
| 33 | 258.2073 | 52.3875 |
| 34 | 257.6601 | 53.975 |
| 35 | 257.1494 | 55.5625 |
| 36 | 256.6727 | 57.15 |
| 37 | 256.2278 | 58.7375 |
| 38 | 255.8126 | 60.325 |
| 39 | 255.425 | 61.9125 |
| 40 | 255.0633 | 63.5 |

# APPENDIX C

# COOLING CURVES DATA

Table 25 Cooling curve data for 7075

| Time | Temp (3) | Temp (8) | Temp (13) | Temp (16) | Temp (22) | Temp (27) | Temp (32) | Temp (40) |
|---|---|---|---|---|---|---|---|---|
| 0 | 763 | 763 | 763 | 763 | 763 | 763 | 763 | 763 |
| 1 | 611.365 | 704.808 | 744.961 | 744.355 | 761.437 | 762.653 | 762.901 | 762.953 |
| 2 | 533.4 | 642.4 | 696.8 | 720.9 | 749.4 | 757.8 | 761.1 | 762.6 |
| 3 | 499.8 | 594.2 | 663.8 | 692.3 | 731.3 | 748.3 | 756.5 | 761.3 |
| 4 | 477.6 | 565.4 | 634.9 | 665.5 | 712 | 735.4 | 748.8 | 758.5 |
| 5 | 461.5 | 543.6 | 611.5 | 642.9 | 693.5 | 721.6 | 739.4 | 754.1 |
| 6 | 449.2 | 526.4 | 592.3 | 623.7 | 676.6 | 707.9 | 729.1 | 748.6 |
| 7 | 439.3 | 512.4 | 576.2 | 607.2 | 661.1 | 694.7 | 718.6 | 742.3 |
| 8 | 431.2 | 500.7 | 562.4 | 592.9 | 647.2 | 682.4 | 708.3 | 735.4 |
| 9 | 424.3 | 490.8 | 550.4 | 580.4 | 634.7 | 670.7 | 698.2 | 728.3 |
| 10 | 418.4 | 482.2 | 540.0 | 569.4 | 623.3 | 659.9 | 688.5 | 721.0 |
| 11 | 413.3 | 474.6 | 530.7 | 559.4 | 612.8 | 649.8 | 679.3 | 713.6 |
| 12 | 408.8 | 467.9 | 522.3 | 550.5 | 603.3 | 640.4 | 670.5 | 706.3 |
| 13 | 404.7 | 461.9 | 514.8 | 542.4 | 594.5 | 631.6 | 662.1 | 699.1 |
| 14 | 401.1 | 456.5 | 508.0 | 535 | 586.3 | 623.3 | 654.0 | 691.9 |
| 15 | 397.8 | 451.5 | 501.8 | 528.2 | 578.8 | 615.5 | 646.3 | 684.9 |
| 16 | 394.8 | 447.0 | 496.0 | 521.9 | 571.7 | 608.2 | 639.0 | 677.9 |
| 17 | 392.1 | 442.9 | 490.7 | 516.1 | 565.0 | 601.2 | 631.9 | 671.1 |
| 18 | 389.5 | 439.0 | 485.8 | 510.6 | 558.8 | 594.5 | 625.1 | 664.4 |
| 19 | 387.2 | 435.4 | 481.1 | 505.4 | 552.5 | 588.2 | 618.5 | 657.8 |
| 20 | 385.0 | 432.1 | 476.8 | 500.6 | 547.2 | 582.1 | 612.2 | 651.4 |
| 21 | 382.9 | 428.9 | 472.6 | 496 | 541.8 | 576.2 | 606.0 | 645.0 |
| 22 | 381.0 | 425.9 | 468.7 | 491.6 | 536.7 | 570.6 | 600.1 | 638.8 |
| 23 | 379.1 | 423.1 | 465.0 | 487.4 | 531.7 | 565.2 | 594.3 | 632.7 |
| 24 | 377.3 | 420.4 | 461.5 | 483.5 | 527.0 | 559.9 | 588.7 | 626.7 |
| 25 | 375.7 | 417.8 | 458.1 | 479.7 | 522.4 | 554.8 | 583.2 | 620.8 |
| 26 | 374.1 | 415.3 | 454.8 | 476 | 518.0 | 549.9 | 577.9 | 615.0 |
| 27 | 372.5 | 412.9 | 451.7 | 472.5 | 513.7 | 545.1 | 572.7 | 609.3 |
| 28 | 371.0 | 410.7 | 448.6 | 469.1 | 509.6 | 540.5 | 567.6 | 603.8 |
| 29 | 369.6 | 408.4 | 445.7 | 465.8 | 505.6 | 535.9 | 562.6 | 598.3 |
| 30 | 368.2 | 406.3 | 442.9 | 462.6 | 501.6 | 531.5 | 557.8 | 592.9 |
| 31 | 366.9 | 404.2 | 440.1 | 459.4 | 497.8 | 527.2 | 553.0 | 587.7 |
| 32 | 365.6 | 402.2 | 437.4 | 456.4 | 494.1 | 522.9 | 548.4 | 582.5 |
| 33 | 364.3 | 400.3 | 434.8 | 453.4 | 490.5 | 518.8 | 543.8 | 577.4 |
| 34 | 363.1 | 398.4 | 432.3 | 450.6 | 486.9 | 514.8 | 539.4 | 572.4 |
| 35 | 361.9 | 396.5 | 429.8 | 447.7 | 483.5 | 510.8 | 535.0 | 567.5 |
| 36 | 360.7 | 394.7 | 427.4 | 445 | 480.1 | 507.0 | 530.8 | 562.7 |
| 37 | 359.6 | 392.9 | 425.0 | 442.3 | 476.8 | 503.2 | 526.6 | 558.0 |
| 38 | 358.5 | 391.2 | 422.7 | 439.7 | 473.5 | 499.5 | 522.4 | 553.3 |
| 39 | 357.4 | 389.5 | 420.4 | 437.1 | 470.3 | 495.9 | 518.4 | 548.8 |
| 40 | 356.4 | 387.9 | 418.2 | 434.6 | 467.2 | 492.3 | 514.5 | 544.3 |
| 41 | 355.3 | 386.3 | 416.0 | 432.1 | 464.2 | 488.8 | 510.6 | 539.9 |
| 42 | 354.3 | 384.7 | 413.9 | 429.7 | 461.2 | 485.4 | 506.8 | 535.6 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 43 | 353.3 | 383.1 | 411.8 | 427.4 | 458.3 | 482.0 | 503.0 | 531.3 |
| 44 | 352.3 | 381.6 | 409.8 | 425 | 455.4 | 478.7 | 499.4 | 527.2 |
| 45 | 351.4 | 380.1 | 407.8 | 422.8 | 452.6 | 475.5 | 495.8 | 523.1 |
| 46 | 350.4 | 378.7 | 405.9 | 420.5 | 449.8 | 472.3 | 492.2 | 519.1 |
| 47 | 349.5 | 377.2 | 403.9 | 418.4 | 447.1 | 469.2 | 488.8 | 515.1 |
| 48 | 348.6 | 375.8 | 402.1 | 416.2 | 444.5 | 466.2 | 485.4 | 511.3 |
| 49 | 347.8 | 374.5 | 400.2 | 414.1 | 441.9 | 463.2 | 482.0 | 507.5 |
| 50 | 346.9 | 373.1 | 398.4 | 412.1 | 439.3 | 460.2 | 478.8 | 503.7 |
| 51 | 346.0 | 371.8 | 396.6 | 410 | 436.8 | 457.3 | 475.5 | 500.1 |
| 52 | 345.2 | 370.5 | 394.9 | 408 | 434.3 | 454.5 | 472.4 | 496.5 |
| 53 | 344.4 | 369.2 | 393.2 | 406.1 | 431.9 | 451.7 | 469.3 | 492.9 |
| 54 | 343.6 | 368.0 | 391.5 | 404.2 | 429.5 | 449.0 | 466.2 | 489.5 |
| 55 | 342.8 | 366.8 | 389.8 | 402.3 | 427.2 | 446.3 | 463.2 | 486.1 |
| 56 | 342.0 | 365.6 | 388.2 | 400.5 | 424.9 | 443.7 | 460.3 | 482.7 |
| 57 | 341.3 | 364.4 | 386.6 | 398.7 | 422.6 | 441.1 | 457.4 | 479.4 |
| 58 | 340.5 | 363.2 | 385.1 | 396.9 | 420.4 | 438.5 | 454.6 | 476.2 |
| 59 | 339.8 | 362.1 | 383.5 | 395.1 | 418.3 | 436.0 | 451.8 | 473.0 |
| 60 | 339.1 | 361.0 | 382.0 | 393.4 | 416.1 | 433.6 | 449.1 | 469.9 |
| 61 | 338.4 | 359.9 | 380.6 | 391.7 | 414.0 | 431.2 | 446.4 | 466.9 |
| 62 | 337.7 | 358.8 | 379.1 | 390.1 | 412.0 | 428.8 | 443.8 | 463.9 |
| 63 | 337.0 | 357.7 | 377.7 | 388.5 | 410.0 | 426.5 | 441.2 | 460.9 |
| 64 | 336.3 | 356.7 | 376.3 | 386.9 | 408.0 | 424.2 | 438.6 | 458.0 |
| 65 | 335.7 | 355.7 | 374.9 | 385.3 | 406.1 | 422.0 | 436.1 | 455.2 |
| 66 | 335.0 | 354.7 | 373.6 | 383.8 | 404.2 | 419.8 | 433.7 | 452.4 |
| 67 | 334.4 | 353.7 | 372.2 | 382.3 | 402.3 | 417.7 | 431.3 | 449.7 |
| 68 | 333.8 | 352.7 | 370.9 | 380.8 | 400.4 | 415.5 | 428.9 | 447.0 |
| 69 | 333.2 | 351.8 | 369.7 | 379.3 | 398.6 | 413.5 | 426.6 | 444.3 |
| 70 | 332.6 | 350.8 | 368.4 | 377.9 | 396.9 | 411.4 | 424.3 | 441.7 |
| 71 | 332.0 | 349.9 | 367.2 | 376.5 | 395.1 | 409.4 | 422.1 | 439.2 |
| 72 | 331.4 | 349.0 | 366.0 | 375.1 | 393.4 | 407.5 | 419.9 | 436.7 |
| 73 | 330.9 | 348.1 | 364.8 | 373.8 | 391.7 | 405.5 | 417.8 | 434.2 |
| 74 | 330.3 | 347.3 | 363.6 | 372.5 | 390.1 | 403.6 | 415.6 | 431.8 |
| 75 | 329.8 | 346.4 | 362.5 | 371.2 | 388.5 | 401.8 | 413.6 | 429.5 |
| 76 | 329.2 | 345.6 | 361.4 | 369.9 | 386.9 | 399.9 | 411.5 | 427.1 |
| 77 | 328.7 | 344.8 | 360.3 | 368.6 | 385.3 | 398.1 | 409.5 | 424.8 |
| 78 | 328.2 | 344.0 | 359.2 | 367.4 | 383.8 | 396.4 | 407.5 | 422.6 |
| 79 | 327.7 | 343.2 | 358.1 | 366.2 | 382.3 | 394.6 | 405.6 | 420.4 |
| 80 | 327.2 | 342.4 | 357.1 | 365 | 380.8 | 392.9 | 403.7 | 418.2 |
| 81 | 326.7 | 341.6 | 356.0 | 363.8 | 379.3 | 391.3 | 401.9 | 416.1 |
| 82 | 326.2 | 340.9 | 355.0 | 362.7 | 377.9 | 389.6 | 400.0 | 414.0 |
| 83 | 325.7 | 340.2 | 354.0 | 361.5 | 376.5 | 388.0 | 398.2 | 412.0 |
| 84 | 325.3 | 339.4 | 353.1 | 360.4 | 375.138 | 386.4 | 396.5 | 410.0 |
| 85 | 324.8 | 338.7 | 352.1 | 359.4 | 373.8 | 384.9 | 394.7 | 408.0 |
| 86 | 324.4 | 338.0 | 351.2 | 358.3 | 372.5 | 383.4 | 393.0 | 406.0 |
| 87 | 323.9 | 337.3 | 350.3 | 357.2 | 371.2 | 381.9 | 391.4 | 404.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 88 | 323.5 | 336.7 | 349.4 | 356.2 | 369.9 | 380.4 | 389.7 | 402.3 |
| 89 | 323.1 | 336.0 | 348.5 | 355.2 | 368.6 | 378.9 | 388.1 | 400.4 |
| 90 | 322.7 | 335.4 | 347.6 | 354.2 | 367.4 | 377.5 | 386.5 | 398.6 |
| 91 | 322.3 | 334.7 | 346.7 | 353.2 | 366.2 | 376.1 | 385.0 | 396.9 |
| 92 | 321.9 | 334.1 | 345.9 | 352.3 | 365.0 | 374.8 | 383.4 | 395.1 |
| 93 | 321.5 | 333.5 | 345.1 | 351.3 | 363.8 | 373.4 | 381.9 | 393.4 |
| 94 | 321.1 | 332.9 | 344.3 | 350.4 | 362.7 | 372.1 | 380.5 | 391.7 |
| 95 | 320.7 | 332.3 | 343.5 | 349.5 | 361.6 | 370.8 | 379.0 | 390.1 |
| 96 | 320.3 | 331.7 | 342.7 | 348.6 | 360.4 | 369.5 | 377.6 | 388.5 |
| 97 | 320.0 | 331.1 | 341.9 | 347.7 | 359.4 | 368.3 | 376.2 | 386.9 |
| 98 | 319.6 | 330.6 | 341.2 | 346.9 | 358.3 | 367.1 | 374.8 | 385.3 |
| 99 | 319.3 | 330.0 | 340.4 | 346 | 357.2 | 365.9 | 373.5 | 383.8 |
| 100 | 318.9 | 329.5 | 339.7 | 345.2 | 356.2 | 364.7 | 372.2 | 382.3 |
| 101 | 318.6 | 329.0 | 339.0 | 344.4 | 355.2 | 363.5 | 370.9 | 380.8 |
| 102 | 318.2 | 328.4 | 338.3 | 343.6 | 354.2 | 362.4 | 369.6 | 379.3 |
| 103 | 317.9 | 327.9 | 337.6 | 342.8 | 353.2 | 361.2 | 368.3 | 377.9 |
| 104 | 317.6 | 327.4 | 336.9 | 342.1 | 352.3 | 360.1 | 367.1 | 376.5 |
| 105 | 317.3 | 326.9 | 336.3 | 341.3 | 351.3 | 359.1 | 365.9 | 375.1 |
| 106 | 317.0 | 326.5 | 335.6 | 340.6 | 350.4 | 358.0 | 364.7 | 373.8 |
| 107 | 316.7 | 326.0 | 335.0 | 339.8 | 349.5 | 357.0 | 363.6 | 372.5 |
| 108 | 316.4 | 325.5 | 334.3 | 339.1 | 348.6 | 355.9 | 362.4 | 371.2 |
| 109 | 316.1 | 325.1 | 333.7 | 338.4 | 347.8 | 354.9 | 361.3 | 369.9 |
| 110 | 315.8 | 324.6 | 333.1 | 337.7 | 346.9 | 353.9 | 360.2 | 368.6 |
| 111 | 315.5 | 324.2 | 332.5 | 337 | 346.1 | 353.0 | 359.1 | 367.4 |
| 112 | 315.2 | 323.7 | 331.9 | 336.4 | 345.2 | 352.0 | 358.1 | 366.2 |
| 113 | 314.9 | 323.3 | 331.4 | 335.7 | 344.4 | 351.1 | 357.0 | 365.0 |
| 114 | 314.7 | 322.9 | 330.8 | 335.1 | 343.6 | 350.2 | 356.0 | 363.8 |
| 115 | 314.4 | 322.5 | 330.2 | 344.4 | 342.8 | 349.3 | 355.0 | 362.7 |
| 116 | 314.1 | 322.1 | 329.7 | 333.8 | 342.1 | 348.4 | 354.0 | 361.6 |
| 117 | 313.9 | 321.7 | 329.2 | 333.2 | 341.3 | 347.5 | 353.0 | 360.5 |
| 118 | 313.6 | 321.3 | 328.6 | 332.6 | 340.6 | 346.7 | 352.1 | 359.4 |
| 119 | 313.4 | 320.9 | 328.1 | 332 | 339.8 | 345.8 | 351.1 | 358.3 |
| 120 | 313.2 | 320.5 | 327.6 | 331.5 | 339.1 | 345.0 | 350.2 | 357.3 |
| 121 | 312.9 | 320.2 | 327.1 | 330.9 | 338.4 | 344.2 | 349.3 | 356.2 |
| 122 | 312.7 | 319.8 | 326.6 | 330.3 | 337.7 | 343.4 | 348.4 | 355.2 |
| 123 | 312.5 | 319.4 | 326.2 | 329.8 | 337.1 | 342.6 | 347.6 | 354.2 |
| 124 | 312.2 | 319.1 | 325.7 | 329.3 | 336.4 | 341.9 | 346.7 | 353.3 |
| 125 | 312.0 | 318.7 | 325.2 | 328.7 | 335.7 | 341.1 | 345.9 | 352.3 |
| 126 | 311.8 | 318.4 | 324.8 | 328.2 | 335.1 | 340.4 | 345.1 | 351.4 |
| 127 | 311.6 | 318.1 | 324.3 | 327.7 | 334.5 | 339.6 | 344.2 | 350.4 |
| 128 | 311.4 | 317.8 | 323.9 | 327.2 | 333.8 | 338.9 | 343.5 | 349.5 |
| 129 | 311.2 | 317.4 | 323.5 | 326.7 | 333.2 | 338.2 | 342.7 | 348.6 |
| 130 | 311.0 | 317.1 | 323.0 | 326.3 | 332.6 | 337.6 | 341.9 | 347.8 |
| 131 | 310.8 | 316.8 | 322.6 | 325.8 | 332.1 | 336.9 | 341.2 | 346.9 |
| 132 | 310.6 | 316.5 | 322.2 | 325.3 | 331.5 | 336.2 | 340.4 | 346.1 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 133 | 310.4 | 316.2 | 321.8 | 324.9 | 330.9 | 335.6 | 339.7 | 345.3 |
| 134 | 310.2 | 315.9 | 321.4 | 324.4 | 330.4 | 334.9 | 339.0 | 344.4 |
| 135 | 310.0 | 315.6 | 321.0 | 324 | 329.8 | 334.3 | 338.3 | 343.6 |
| 136 | 309.8 | 315.4 | 320.7 | 323.5 | 329.3 | 333.7 | 337.6 | 342.9 |
| 137 | 309.7 | 315.1 | 320.3 | 323.1 | 328.8 | 333.1 | 336.9 | 342.1 |
| 138 | 309.5 | 314.8 | 319.9 | 322.7 | 328.2 | 332.5 | 336.3 | 341.3 |
| 139 | 309.3 | 314.5 | 319.6 | 322.3 | 327.7 | 331.9 | 335.6 | 340.6 |
| 140 | 309.2 | 314.3 | 319.2 | 321.9 | 327.2 | 331.3 | 335.0 | 339.9 |
| 141 | 309.0 | 314.0 | 318.9 | 321.5 | 326.7 | 330.8 | 334.3 | 339.2 |
| 142 | 308.8 | 313.8 | 318.5 | 321.1 | 326.3 | 330.2 | 333.7 | 338.5 |
| 143 | 308.7 | 313.5 | 318.2 | 320.7 | 325.8 | 329.7 | 333.1 | 337.8 |
| 144 | 308.5 | 313.3 | 317.9 | 320.4 | 325.3 | 329.1 | 332.5 | 337.1 |
| 145 | 308.4 | 313.0 | 317.6 | 320 | 324.9 | 328.6 | 331.9 | 336.4 |
| 146 | 308.2 | 312.8 | 317.2 | 319.6 | 324.4 | 328.1 | 331.4 | 335.8 |
| 147 | 308.1 | 312.6 | 316.9 | 319.3 | 324.0 | 327.6 | 330.8 | 335.1 |
| 148 | 307.9 | 312.4 | 316.6 | 318.9 | 323.6 | 327.1 | 330.3 | 334.5 |
| 149 | 307.8 | 312.1 | 316.3 | 318.6 | 323.1 | 326.6 | 329.7 | 333.9 |
| 150 | 307.6 | 311.9 | 316.0 | 318.3 | 322.7 | 326.2 | 329.2 | 333.3 |
| 151 | 307.5 | 311.7 | 315.8 | 317.9 | 322.3 | 325.7 | 328.7 | 332.7 |
| 152 | 307.4 | 311.5 | 315.5 | 317.6 | 321.9 | 325.2 | 328.2 | 332.1 |
| 153 | 307.2 | 311.3 | 315.2 | 317.3 | 321.5 | 324.8 | 327.7 | 331.5 |
| 154 | 307.1 | 311.1 | 314.9 | 317 | 321.1 | 324.3 | 327.2 | 331.0 |
| 155 | 307.0 | 310.9 | 314.7 | 316.7 | 320.8 | 323.9 | 326.7 | 330.4 |
| 156 | 306.9 | 310.7 | 314.4 | 316.4 | 320.4 | 323.5 | 326.2 | 329.9 |
| 157 | 306.7 | 310.5 | 314.136 | 316.1 | 320.0 | 323.0 | 325.7 | 329.3 |
| 158 | 306.6 | 310.3 | 313.9 | 315.8 | 319.7 | 322.6 | 325.3 | 328.8 |
| 159 | 306.5 | 310.1 | 313.6 | 315.5 | 319.3 | 322.2 | 324.8 | 328.3 |
| 160 | 306.4 | 309.9 | 313.4 | 315.3 | 319.0 | 321.8 | 324.4 | 327.8 |

Table 26 Cooling curve data for 6061

| Time | Temp (3) | Temp (8) | Temp (13) | Temp (16) | Temp (22) | Temp (27) | Temp (32) | Temp (40) |
|---|---|---|---|---|---|---|---|---|
| 0 | 803 | 803 | 803 | 803 | 803 | 803 | 803 | 803 |
| 1 | 625.415 | 733.045 | 780.811 | 792.2505 | 801.021 | 802.56 | 802.881 | 802.948 |
| 2 | 559.066 | 667.12 | 736.383 | 760.717 | 788.695 | 797.841 | 801.207 | 802.591 |
| 3 | 522.371 | 623.425 | 697.702 | 727.9245 | 769.445 | 787.394 | 796.115 | 801.214 |
| 4 | 498.072 | 592.241 | 666.615 | 699.2905 | 748.789 | 773.738 | 787.94 | 798.211 |
| 5 | 480.397 | 568.605 | 641.432 | 674.9725 | 729.003 | 758.992 | 777.878 | 793.599 |
| 6 | 466.781 | 549.904 | 620.64 | 654.2755 | 710.794 | 744.299 | 766.923 | 787.716 |
| 7 | 455.859 | 534.626 | 603.141 | 636.4815 | 694.253 | 730.18 | 755.708 | 780.949 |
| 8 | 446.838 | 521.836 | 588.166 | 621.0115 | 679.275 | 716.847 | 744.598 | 773.615 |
| 9 | 439.221 | 510.924 | 575.173 | 607.4265 | 665.701 | 704.363 | 733.798 | 765.954 |
| 10 | 432.675 | 501.469 | 563.762 | 595.38 | 653.357 | 692.708 | 723.404 | 758.129 |
| 11 | 426.969 | 493.169 | 553.635 | 584.602 | 642.081 | 681.828 | 713.45 | 750.248 |
| 12 | 421.934 | 485.804 | 544.564 | 574.884 | 631.733 | 671.656 | 703.94 | 742.384 |
| 13 | 417.446 | 479.207 | 536.374 | 566.0585 | 622.192 | 662.125 | 694.856 | 734.583 |
| 14 | 413.409 | 473.249 | 528.926 | 557.993 | 613.356 | 653.17 | 686.176 | 726.875 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 15 | 409.75 | 467.828 | 522.108 | 550.5765 | 605.133 | 644.731 | 677.871 | 719.277 |
| 16 | 406.411 | 462.863 | 515.827 | 543.7145 | 597.441 | 636.745 | 669.907 | 711.799 |
| 17 | 403.342 | 458.286 | 510.006 | 537.332 | 590.217 | 629.166 | 662.254 | 704.444 |
| 18 | 400.506 | 454.042 | 504.584 | 531.366 | 583.402 | 621.948 | 654.886 | 697.216 |
| 19 | 397.869 | 450.087 | 499.508 | 525.763 | 576.949 | 615.054 | 647.778 | 690.115 |
| 20 | 395.405 | 446.382 | 494.734 | 520.478 | 570.816 | 608.45 | 640.908 | 683.141 |
| 21 | 393.092 | 442.895 | 490.225 | 515.4735 | 564.967 | 602.107 | 634.257 | 676.292 |
| 22 | 390.911 | 439.6 | 485.949 | 510.7155 | 559.372 | 596 | 627.807 | 669.566 |
| 23 | 388.845 | 436.474 | 481.879 | 506.1765 | 554.004 | 590.107 | 621.543 | 662.962 |
| 24 | 386.882 | 433.498 | 477.992 | 501.834 | 548.84 | 584.408 | 615.451 | 656.477 |
| 25 | 385.01 | 430.654 | 474.27 | 497.6655 | 543.861 | 578.888 | 609.52 | 650.109 |
| 26 | 383.206 | 427.924 | 470.697 | 493.6615 | 539.058 | 573.539 | 603.745 | 643.857 |
| 27 | 381.484 | 425.303 | 467.254 | 489.796 | 534.405 | 568.338 | 598.109 | 637.717 |
| 28 | 379.829 | 422.78 | 463.93 | 486.0585 | 529.89 | 563.276 | 592.604 | 631.688 |
| 29 | 378.232 | 420.344 | 460.716 | 482.44 | 525.504 | 558.345 | 587.225 | 625.767 |
| 30 | 376.689 | 417.987 | 457.601 | 478.9285 | 521.238 | 553.535 | 581.965 | 619.953 |
| 31 | 375.198 | 415.703 | 454.578 | 475.5175 | 517.083 | 548.841 | 576.819 | 614.244 |
| 32 | 373.75 | 413.487 | 451.639 | 472.199 | 513.033 | 544.255 | 571.781 | 608.636 |
| 33 | 372.343 | 411.332 | 448.78 | 468.967 | 509.081 | 539.772 | 566.848 | 603.129 |
| 34 | 370.975 | 409.235 | 445.994 | 465.8165 | 505.221 | 535.388 | 562.015 | 597.721 |
| 35 | 369.643 | 407.191 | 443.277 | 462.742 | 501.449 | 531.097 | 557.279 | 592.409 |
| 36 | 368.344 | 405.198 | 440.625 | 459.7395 | 497.761 | 526.896 | 552.637 | 587.193 |
| 37 | 367.076 | 403.251 | 438.034 | 456.8045 | 494.153 | 522.783 | 548.086 | 582.07 |
| 38 | 365.837 | 401.35 | 435.502 | 453.9345 | 490.621 | 518.752 | 543.623 | 577.039 |
| 39 | 364.627 | 399.491 | 433.025 | 451.1265 | 487.162 | 514.802 | 539.245 | 572.098 |
| 40 | 363.444 | 397.673 | 430.601 | 448.378 | 483.773 | 510.929 | 534.95 | 567.245 |
| 41 | 362.286 | 395.894 | 428.227 | 445.6865 | 480.452 | 507.132 | 530.736 | 562.479 |
| 42 | 361.154 | 394.152 | 425.903 | 443.049 | 477.197 | 503.407 | 526.6 | 557.797 |
| 43 | 360.044 | 392.445 | 423.625 | 440.4645 | 474.005 | 499.753 | 522.541 | 553.2 |
| 44 | 358.957 | 390.773 | 421.393 | 437.931 | 470.875 | 496.169 | 518.558 | 548.685 |
| 45 | 357.892 | 389.135 | 419.205 | 435.447 | 467.805 | 492.651 | 514.647 | 544.25 |
| 46 | 356.846 | 387.528 | 417.059 | 433.011 | 464.793 | 489.2 | 510.809 | 539.894 |
| 47 | 355.822 | 385.952 | 414.954 | 430.621 | 461.838 | 485.813 | 507.041 | 535.617 |
| 48 | 354.817 | 384.406 | 412.889 | 428.2765 | 458.937 | 482.488 | 503.341 | 531.416 |
| 49 | 353.832 | 382.89 | 410.863 | 425.9765 | 456.091 | 479.223 | 499.709 | 527.289 |
| 50 | 352.866 | 381.403 | 408.876 | 423.719 | 453.297 | 476.019 | 496.142 | 523.237 |
| 51 | 351.918 | 379.944 | 406.925 | 421.503 | 450.555 | 472.873 | 492.64 | 519.257 |
| 52 | 350.987 | 378.512 | 405.011 | 419.3285 | 447.862 | 469.784 | 489.201 | 515.347 |
| 53 | 350.074 | 377.106 | 403.131 | 417.1935 | 445.219 | 466.751 | 485.823 | 511.508 |
| 54 | 349.174 | 375.725 | 401.287 | 415.0985 | 442.625 | 463.774 | 482.508 | 507.737 |
| 55 | 348.293 | 374.369 | 399.476 | 413.0415 | 440.078 | 460.851 | 479.252 | 504.034 |
| 56 | 347.429 | 373.039 | 397.697 | 411.021 | 437.576 | 457.981 | 476.055 | 500.397 |
| 57 | 346.581 | 371.734 | 395.952 | 409.038 | 435.12 | 455.161 | 472.915 | 496.825 |
| 58 | 345.749 | 370.452 | 394.238 | 407.0905 | 432.708 | 452.393 | 469.831 | 493.317 |
| 59 | 344.931 | 369.194 | 392.555 | 405.1785 | 430.34 | 449.674 | 466.802 | 489.87 |
| 60 | 344.129 | 367.958 | 390.903 | 403.301 | 428.014 | 447.004 | 463.827 | 486.486 |
| 61 | 343.34 | 366.744 | 389.28 | 401.4575 | 425.73 | 444.383 | 460.906 | 483.163 |
| 62 | 342.566 | 365.553 | 387.686 | 399.647 | 423.487 | 441.808 | 458.038 | 479.899 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 63 | 341.807 | 364.383 | 386.122 | 397.869 | 421.285 | 439.279 | 455.22 | 476.693 |
| 64 | 341.059 | 363.233 | 384.585 | 396.123 | 419.122 | 436.796 | 452.454 | 473.544 |
| 65 | 340.326 | 362.105 | 383.076 | 394.4085 | 416.998 | 434.357 | 449.737 | 470.452 |
| 66 | 339.606 | 360.997 | 381.594 | 392.7245 | 414.912 | 431.963 | 447.068 | 467.415 |
| 67 | 338.899 | 359.909 | 380.139 | 391.0715 | 412.863 | 429.61 | 444.447 | 464.432 |
| 68 | 338.206 | 358.84 | 378.71 | 389.4475 | 410.851 | 427.3 | 441.873 | 461.502 |
| 69 | 337.524 | 357.791 | 377.307 | 387.8525 | 408.875 | 425.031 | 439.344 | 458.624 |
| 70 | 336.855 | 356.76 | 375.928 | 386.287 | 406.934 | 422.803 | 436.861 | 455.798 |
| 71 | 336.198 | 355.749 | 374.575 | 384.7485 | 405.028 | 420.614 | 434.422 | 453.022 |
| 72 | 335.553 | 354.755 | 373.245 | 383.238 | 403.156 | 418.464 | 432.026 | 450.295 |
| 73 | 334.919 | 353.779 | 371.94 | 381.754 | 401.318 | 416.353 | 429.674 | 447.617 |
| 74 | 334.296 | 352.82 | 370.657 | 380.2965 | 399.512 | 414.279 | 427.363 | 444.987 |
| 75 | 333.685 | 351.879 | 369.398 | 378.8655 | 397.738 | 412.243 | 425.093 | 442.403 |
| 76 | 333.085 | 350.954 | 368.161 | 377.46 | 395.997 | 410.242 | 422.864 | 439.866 |
| 77 | 332.495 | 350.046 | 366.946 | 376.0795 | 394.286 | 408.278 | 420.674 | 437.373 |
| 78 | 331.916 | 349.154 | 365.753 | 374.7235 | 392.606 | 406.348 | 418.524 | 434.926 |
| 79 | 331.347 | 348.278 | 364.581 | 373.392 | 390.955 | 404.453 | 416.412 | 432.521 |
| 80 | 330.788 | 347.417 | 363.43 | 372.084 | 389.334 | 402.592 | 414.338 | 430.16 |
| 81 | 330.24 | 346.572 | 362.3 | 370.7995 | 387.742 | 400.764 | 412.3 | 427.841 |
| 82 | 329.701 | 345.742 | 361.19 | 369.5375 | 386.179 | 398.968 | 410.299 | 425.563 |
| 83 | 329.172 | 344.927 | 360.099 | 368.299 | 384.643 | 397.204 | 408.334 | 423.325 |
| 84 | 328.652 | 344.127 | 359.028 | 367.082 | 383.135 | 395.472 | 406.403 | 421.128 |
| 85 | 328.141 | 343.34 | 357.977 | 365.8865 | 381.653 | 393.771 | 404.507 | 418.969 |
| 86 | 327.64 | 342.568 | 356.943 | 364.712 | 380.198 | 392.1 | 402.645 | 416.85 |
| 87 | 327.147 | 341.809 | 355.929 | 363.559 | 378.769 | 390.459 | 400.816 | 414.767 |
| 88 | 326.663 | 341.064 | 354.932 | 362.426 | 377.366 | 388.847 | 399.019 | 412.722 |
| 89 | 326.188 | 340.333 | 353.953 | 361.314 | 375.987 | 387.264 | 397.255 | 410.714 |
| 90 | 325.721 | 339.613 | 352.991 | 360.221 | 374.633 | 385.709 | 395.522 | 408.742 |
| 91 | 325.262 | 338.907 | 352.047 | 359.148 | 373.303 | 384.182 | 393.821 | 406.805 |
| 92 | 324.812 | 338.214 | 351.119 | 358.094 | 371.997 | 382.683 | 392.15 | 404.903 |
| 93 | 324.37 | 337.533 | 350.208 | 357.0585 | 370.714 | 381.21 | 390.508 | 403.034 |
| 94 | 323.935 | 336.864 | 349.314 | 356.042 | 369.454 | 379.763 | 388.896 | 401.199 |
| 95 | 323.509 | 336.207 | 348.435 | 355.0435 | 368.217 | 378.342 | 387.312 | 399.396 |
| 96 | 323.09 | 335.562 | 347.572 | 354.0625 | 367.002 | 376.946 | 385.757 | 397.626 |
| 97 | 322.679 | 334.928 | 346.724 | 353.0995 | 365.808 | 375.575 | 384.229 | 395.887 |
| 98 | 322.275 | 334.306 | 345.892 | 352.1535 | 364.636 | 374.229 | 382.729 | 394.179 |
| 99 | 321.878 | 333.695 | 345.074 | 351.224 | 363.484 | 372.907 | 381.255 | 392.502 |
| 100 | 321.488 | 333.094 | 344.271 | 350.312 | 362.353 | 371.608 | 379.808 | 390.854 |
| 101 | 321.105 | 332.505 | 343.483 | 349.4155 | 361.243 | 370.333 | 378.386 | 389.236 |
| 102 | 320.729 | 331.926 | 342.708 | 348.535 | 360.152 | 369.08 | 376.99 | 387.646 |
| 103 | 320.36 | 331.357 | 341.947 | 347.6705 | 359.08 | 367.849 | 375.619 | 386.085 |
| 104 | 319.997 | 330.798 | 341.2 | 346.8215 | 358.028 | 366.641 | 374.272 | 384.552 |
| 105 | 319.641 | 330.25 | 340.466 | 345.9875 | 356.994 | 365.454 | 372.949 | 383.046 |
| 106 | 319.291 | 329.711 | 339.745 | 345.1685 | 355.979 | 364.288 | 371.649 | 381.566 |
| 107 | 318.947 | 329.182 | 339.037 | 344.364 | 354.982 | 363.143 | 370.373 | 380.114 |
| 108 | 318.61 | 328.662 | 338.342 | 343.5735 | 354.002 | 362.018 | 369.12 | 378.687 |
| 109 | 318.278 | 328.151 | 337.659 | 342.7975 | 353.04 | 360.913 | 367.888 | 377.285 |
| 110 | 317.953 | 327.65 | 336.988 | 342.0345 | 352.096 | 359.828 | 366.679 | 375.908 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 111 | 317.633 | 327.157 | 336.329 | 341.286 | 351.168 | 358.762 | 365.491 | 374.556 |
| 112 | 317.319 | 326.673 | 335.682 | 340.551 | 350.256 | 357.716 | 364.325 | 373.228 |
| 113 | 317.01 | 326.198 | 335.047 | 339.8285 | 349.361 | 356.688 | 363.179 | 371.924 |
| 114 | 316.707 | 325.732 | 334.422 | 339.119 | 348.482 | 355.678 | 362.054 | 370.643 |
| 115 | 316.41 | 325.273 | 333.809 | 338.422 | 347.618 | 354.686 | 360.949 | 369.384 |
| 116 | 316.117 | 324.823 | 333.207 | 337.738 | 346.77 | 353.712 | 359.863 | 368.149 |
| 117 | 315.83 | 324.38 | 332.615 | 337.0655 | 345.937 | 352.756 | 358.797 | 366.935 |
| 118 | 315.547 | 323.945 | 332.033 | 336.4045 | 345.119 | 351.817 | 357.751 | 365.745 |
| 119 | 315.269 | 323.518 | 331.462 | 335.7555 | 344.315 | 350.894 | 356.723 | 364.575 |
| 120 | 314.997 | 323.098 | 330.901 | 335.1185 | 343.526 | 349.988 | 355.714 | 363.427 |
| 121 | 314.73 | 322.687 | 330.351 | 334.493 | 342.751 | 349.099 | 354.722 | 362.298 |
| 122 | 314.467 | 322.283 | 329.81 | 333.8785 | 341.99 | 348.225 | 353.749 | 361.19 |
| 123 | 314.209 | 321.886 | 329.279 | 333.2755 | 341.242 | 347.366 | 352.792 | 360.101 |
| 124 | 313.956 | 321.496 | 328.758 | 332.683 | 340.508 | 346.523 | 351.853 | 359.032 |
| 125 | 313.708 | 321.113 | 328.246 | 332.101 | 339.787 | 345.695 | 350.93 | 357.982 |
| 126 | 313.464 | 320.737 | 327.743 | 331.5295 | 339.079 | 344.882 | 350.024 | 356.95 |
| 127 | 313.224 | 320.368 | 327.249 | 330.9685 | 338.384 | 344.083 | 349.133 | 355.937 |
| 128 | 312.989 | 320.005 | 326.764 | 330.417 | 337.7 | 343.299 | 348.259 | 354.942 |
| 129 | 312.757 | 319.649 | 326.288 | 329.876 | 337.029 | 342.528 | 347.4 | 353.964 |
| 130 | 312.53 | 319.3 | 325.82 | 329.344 | 336.37 | 341.771 | 346.557 | 353.004 |
| 131 | 312.307 | 318.956 | 325.36 | 328.8215 | 335.723 | 341.028 | 345.728 | 352.061 |
| 132 | 312.088 | 318.619 | 324.909 | 328.3085 | 335.087 | 340.298 | 344.915 | 351.134 |
| 133 | 311.873 | 318.287 | 324.466 | 327.805 | 334.463 | 339.581 | 344.116 | 350.225 |
| 134 | 311.662 | 317.962 | 324.03 | 327.3105 | 333.85 | 338.877 | 343.331 | 349.331 |
| 135 | 311.454 | 317.642 | 323.603 | 326.824 | 333.247 | 338.185 | 342.56 | 348.453 |
| 136 | 311.25 | 317.328 | 323.183 | 326.347 | 332.656 | 337.505 | 341.802 | 347.591 |
| 137 | 311.049 | 317.019 | 322.769 | 325.8775 | 332.075 | 336.839 | 341.059 | 346.746 |
| 138 | 310.851 | 316.715 | 322.363 | 325.4165 | 331.504 | 336.184 | 340.33 | 345.915 |
| 139 | 310.657 | 316.417 | 321.965 | 324.964 | 330.944 | 335.541 | 339.614 | 345.1 |
| 140 | 310.467 | 316.124 | 321.574 | 324.52 | 330.394 | 334.909 | 338.91 | 344.299 |
| 141 | 310.281 | 315.837 | 321.19 | 324.0835 | 329.853 | 334.288 | 338.218 | 343.512 |
| 142 | 310.098 | 315.555 | 320.813 | 323.655 | 329.322 | 333.679 | 337.539 | 342.739 |
| 143 | 309.918 | 315.278 | 320.442 | 323.234 | 328.801 | 333.08 | 336.872 | 341.98 |
| 144 | 309.742 | 315.006 | 320.079 | 322.821 | 328.289 | 332.492 | 336.217 | 341.234 |
| 145 | 309.568 | 314.739 | 319.722 | 322.4155 | 327.786 | 331.915 | 335.573 | 340.502 |
| 146 | 309.398 | 314.477 | 319.371 | 322.017 | 327.292 | 331.348 | 334.941 | 339.782 |
| 147 | 309.231 | 314.22 | 319.027 | 321.625 | 326.807 | 330.791 | 334.32 | 339.076 |
| 148 | 309.067 | 313.967 | 318.689 | 321.241 | 326.331 | 330.243 | 333.711 | 338.381 |
| 149 | 308.906 | 313.719 | 318.356 | 320.863 | 325.863 | 329.706 | 333.112 | 337.7 |
| 150 | 308.747 | 313.475 | 318.03 | 320.4925 | 325.403 | 329.178 | 332.523 | 337.03 |
| 151 | 308.592 | 313.236 | 317.71 | 320.1285 | 324.952 | 328.66 | 331.946 | 336.372 |
| 152 | 308.438 | 312.999 | 317.394 | 319.7705 | 324.509 | 328.151 | 331.379 | 335.727 |
| 153 | 308.286 | 312.767 | 317.084 | 319.4185 | 324.074 | 327.652 | 330.823 | 335.094 |
| 154 | 308.138 | 312.539 | 316.78 | 319.0735 | 323.646 | 327.161 | 330.276 | 334.472 |
| 155 | 307.993 | 312.316 | 316.482 | 318.734 | 323.226 | 326.679 | 329.739 | 333.861 |
| 156 | 307.851 | 312.097 | 316.189 | 318.401 | 322.814 | 326.206 | 329.212 | 333.261 |
| 157 | 307.712 | 311.882 | 315.901 | 318.0745 | 322.409 | 325.741 | 328.694 | 332.671 |
| 158 | 307.574 | 311.67 | 315.619 | 317.7535 | 322.011 | 325.284 | 328.185 | 332.092 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 159 | 307.44 | 311.463 | 315.341 | 317.438 | 321.62 | 324.836 | 327.685 | 331.523 |
| 160 | 307.308 | 311.26 | 315.069 | 317.129 | 321.237 | 324.395 | 327.194 | 330.964 |

Table 27 Cooling curve data for A356

| Time | Temp (3) | Temp (8) | Temp (13) | Temp (16) | Temp (22) | Temp (27) | Temp (32) | Temp (40) |
|---|---|---|---|---|---|---|---|---|
| 0 | 813 | 813 | 813 | 813 | 813 | 813 | 813 | 813 |
| 1 | *626.5* | 739.3 | 789.6 | 801.649 | 810.9 | 812.5 | 812.876 | 812.947 |
| 2 | 558.394 | 670.814 | 743.143 | 768.617 | 797.961 | 807.573 | 811.117 | 812.576 |
| 3 | 521.108 | 625.799 | 703.016 | 734.5075 | 777.86 | 796.642 | 805.782 | 811.134 |
| 4 | 496.556 | 593.863 | 670.945 | 704.8805 | 756.388 | 782.409 | 797.245 | 807.995 |
| 5 | 478.773 | 569.751 | 645.064 | 679.816 | 735.899 | 767.094 | 786.773 | 803.184 |
| 6 | 465.112 | 550.728 | 623.758 | 658.5445 | 717.097 | 751.877 | 775.402 | 797.061 |
| 7 | 454.181 | 535.222 | 605.869 | 640.3015 | 700.059 | 737.291 | 763.788 | 790.033 |
| 8 | 445.168 | 522.265 | 590.588 | 624.47 | 684.66 | 723.544 | 752.306 | 782.431 |
| 9 | 437.569 | 511.226 | 577.348 | 610.587 | 670.724 | 710.69 | 741.161 | 774.502 |
| 10 | 431.046 | 501.673 | 565.737 | 598.294 | 658.071 | 698.709 | 730.451 | 766.414 |
| 11 | 425.366 | 493.296 | 555.442 | 587.308 | 646.526 | 687.538 | 720.207 | 758.279 |
| 12 | 420.358 | 485.87 | 546.23 | 577.4115 | 635.942 | 677.104 | 710.429 | 750.168 |
| 13 | 415.898 | 479.222 | 537.919 | 568.431 | 626.191 | 667.335 | 701.098 | 742.13 |
| 14 | 411.889 | 473.222 | 530.365 | 560.227 | 617.163 | 658.161 | 692.185 | 734.191 |
| 15 | 408.255 | 467.766 | 523.454 | 552.688 | 608.769 | 649.522 | 683.664 | 726.372 |
| 16 | 404.941 | 462.77 | 517.091 | 545.7185 | 600.923 | 641.354 | 675.499 | 718.682 |
| 17 | 401.897 | 458.168 | 511.197 | 539.238 | 593.557 | 633.605 | 667.657 | 711.123 |
| 18 | 399.085 | 453.901 | 505.708 | 533.183 | 586.611 | 626.228 | 660.11 | 703.697 |
| 19 | 396.47 | 449.926 | 500.571 | 527.498 | 580.035 | 619.184 | 652.832 | 696.405 |
| 20 | 394.028 | 446.203 | 495.741 | 522.1365 | 573.787 | 612.438 | 645.8 | 689.246 |
| 21 | 391.736 | 442.7 | 491.179 | 517.0595 | 567.83 | 605.961 | 638.993 | 682.217 |
| 22 | 389.574 | 439.39 | 486.854 | 512.2345 | 562.132 | 599.726 | 632.394 | 675.318 |
| 23 | 387.527 | 436.25 | 482.738 | 507.632 | 556.666 | 593.71 | 625.986 | 668.545 |
| 24 | 385.582 | 433.26 | 478.807 | 503.2285 | 551.409 | 587.893 | 619.757 | 661.896 |
| 25 | 383.726 | 430.403 | 475.043 | 499.0025 | 546.34 | 582.26 | 613.692 | 655.369 |
| 26 | 381.951 | 427.666 | 471.426 | 494.9365 | 541.443 | 576.794 | 607.783 | 648.961 |
| 27 | 380.247 | 425.036 | 467.944 | 491.0155 | 536.703 | 571.484 | 602.018 | 642.671 |
| 28 | 378.608 | 422.502 | 464.583 | 487.226 | 532.106 | 566.318 | 596.39 | 636.495 |
| 29 | 377.027 | 420.056 | 461.333 | 483.5565 | 527.642 | 561.286 | 590.892 | 630.431 |
| 30 | 375.499 | 417.689 | 458.183 | 479.998 | 523.3 | 556.38 | 585.518 | 624.478 |
| 31 | 374.006 | 415.389 | 455.128 | 476.543 | 519.078 | 551.598 | 580.264 | 618.634 |
| 32 | 372.568 | 413.158 | 452.156 | 473.1805 | 514.96 | 546.925 | 575.122 | 612.897 |
| 33 | 371.172 | 410.992 | 449.264 | 469.905 | 510.941 | 542.357 | 570.086 | 607.263 |
| 34 | 369.815 | 408.885 | 446.447 | 466.712 | 507.016 | 537.889 | 565.153 | 601.731 |
| 35 | 368.495 | 406.831 | 443.7 | 463.596 | 503.18 | 533.516 | 560.319 | 596.299 |
| 36 | 367.207 | 404.829 | 441.019 | 460.553 | 499.43 | 529.236 | 555.581 | 590.965 |
| 37 | 365.951 | 402.875 | 438.4 | 457.58 | 495.76 | 525.044 | 550.936 | 585.727 |
| 38 | 364.724 | 400.966 | 435.84 | 454.6725 | 492.169 | 520.937 | 546.381 | 580.583 |
| 39 | 363.524 | 399.098 | 433.337 | 451.8275 | 488.652 | 516.913 | 541.915 | 575.534 |
| 40 | 362.351 | 397.272 | 430.887 | 449.043 | 485.208 | 512.968 | 537.534 | 570.575 |
| 41 | 361.204 | 395.486 | 428.488 | 446.316 | 481.832 | 509.101 | 533.235 | 565.705 |
| 42 | 360.082 | 393.736 | 426.139 | 443.645 | 478.524 | 505.308 | 529.018 | 560.923 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 43 | 358.983 | 392.023 | 423.838 | 441.0275 | 475.28 | 501.588 | 524.879 | 556.228 |
| 44 | 357.906 | 390.345 | 421.583 | 438.462 | 472.1 | 497.938 | 520.818 | 551.617 |
| 45 | 356.851 | 388.7 | 419.372 | 435.9465 | 468.98 | 494.358 | 516.831 | 547.089 |
| 46 | 355.816 | 387.088 | 417.205 | 433.48 | 465.92 | 490.844 | 512.919 | 542.643 |
| 47 | 354.802 | 385.506 | 415.079 | 431.061 | 462.918 | 487.397 | 509.078 | 538.276 |
| 48 | 353.806 | 383.955 | 412.994 | 428.688 | 459.973 | 484.014 | 505.309 | 533.989 |
| 49 | 352.831 | 382.434 | 410.948 | 426.36 | 457.083 | 480.693 | 501.608 | 529.779 |
| 50 | 351.874 | 380.942 | 408.941 | 424.0755 | 454.246 | 477.433 | 497.975 | 525.645 |
| 51 | 350.935 | 379.478 | 406.972 | 421.834 | 451.462 | 474.234 | 494.409 | 521.585 |
| 52 | 350.014 | 378.041 | 405.04 | 419.634 | 448.729 | 471.093 | 490.907 | 517.599 |
| 53 | 349.111 | 376.632 | 403.144 | 417.4745 | 446.047 | 468.009 | 487.468 | 513.684 |
| 54 | 348.224 | 375.248 | 401.282 | 415.355 | 443.414 | 464.982 | 484.092 | 509.839 |
| 55 | 347.351 | 373.89 | 399.455 | 413.2755 | 440.829 | 462.01 | 480.778 | 506.064 |
| 56 | 346.495 | 372.556 | 397.662 | 411.233 | 438.292 | 459.093 | 477.525 | 502.358 |
| 57 | 345.655 | 371.247 | 395.901 | 409.2285 | 435.801 | 456.229 | 474.33 | 498.718 |
| 58 | 344.832 | 369.962 | 394.172 | 407.2605 | 433.356 | 453.416 | 471.193 | 495.144 |
| 59 | 344.024 | 368.701 | 392.476 | 405.3275 | 430.954 | 450.655 | 468.112 | 491.634 |
| 60 | 343.231 | 367.463 | 390.81 | 403.4305 | 428.596 | 447.943 | 465.087 | 488.187 |
| 61 | 342.452 | 366.248 | 389.174 | 401.5685 | 426.281 | 445.28 | 462.116 | 484.802 |
| 62 | 341.687 | 365.055 | 387.568 | 399.7395 | 424.008 | 442.666 | 459.2 | 481.479 |
| 63 | 340.936 | 363.883 | 385.992 | 397.9435 | 421.776 | 440.099 | 456.336 | 478.215 |
| 64 | 340.199 | 362.732 | 384.443 | 396.1805 | 419.585 | 437.578 | 453.524 | 475.011 |
| 65 | 339.474 | 361.603 | 382.923 | 394.4495 | 417.433 | 435.103 | 450.763 | 471.864 |
| 66 | 338.762 | 360.493 | 381.431 | 392.75 | 415.32 | 432.673 | 448.052 | 468.774 |
| 67 | 338.064 | 359.404 | 379.965 | 391.081 | 413.246 | 430.287 | 445.389 | 465.739 |
| 68 | 337.379 | 358.335 | 378.526 | 389.442 | 411.209 | 427.944 | 442.775 | 462.759 |
| 69 | 336.706 | 357.285 | 377.113 | 387.8325 | 409.208 | 425.643 | 440.207 | 459.833 |
| 70 | 336.046 | 356.255 | 375.726 | 386.2525 | 407.244 | 423.383 | 437.686 | 456.959 |
| 71 | 335.397 | 355.243 | 374.364 | 384.701 | 405.315 | 421.164 | 435.21 | 454.137 |
| 72 | 334.76 | 354.249 | 373.026 | 383.1775 | 403.421 | 418.985 | 432.779 | 451.366 |
| 73 | 334.135 | 353.273 | 371.713 | 381.6815 | 401.561 | 416.845 | 430.391 | 448.644 |
| 74 | 333.521 | 352.315 | 370.423 | 380.212 | 399.734 | 414.744 | 428.046 | 445.971 |
| 75 | 332.918 | 351.374 | 369.156 | 378.77 | 397.941 | 412.681 | 425.744 | 443.347 |
| 76 | 332.326 | 350.45 | 367.913 | 377.353 | 396.18 | 410.654 | 423.483 | 440.769 |
| 77 | 331.745 | 349.543 | 366.691 | 375.962 | 394.45 | 408.665 | 421.262 | 438.238 |
| 78 | 331.174 | 348.652 | 365.492 | 374.596 | 392.752 | 406.711 | 419.082 | 435.753 |
| 79 | 330.613 | 347.777 | 364.314 | 373.2545 | 391.084 | 404.792 | 416.941 | 433.312 |
| 80 | 330.063 | 346.918 | 363.158 | 371.9375 | 389.446 | 402.907 | 414.838 | 430.915 |
| 81 | 329.522 | 346.074 | 362.022 | 370.6435 | 387.837 | 401.057 | 412.773 | 428.561 |
| 82 | 328.991 | 345.245 | 360.907 | 369.3735 | 386.258 | 399.24 | 410.745 | 426.249 |
| 83 | 328.47 | 344.432 | 359.811 | 368.126 | 384.707 | 397.455 | 408.754 | 423.979 |
| 84 | 327.958 | 343.633 | 358.736 | 366.901 | 383.184 | 395.703 | 406.799 | 421.75 |
| 85 | 327.455 | 342.848 | 357.68 | 365.698 | 381.688 | 393.982 | 404.878 | 419.561 |
| 86 | 326.961 | 342.078 | 356.643 | 364.5165 | 380.219 | 392.292 | 402.993 | 417.411 |
| 87 | 326.477 | 341.321 | 355.624 | 363.3565 | 378.777 | 390.633 | 401.141 | 415.3 |
| 88 | 326.001 | 340.578 | 354.624 | 362.217 | 377.36 | 389.003 | 399.322 | 413.227 |
| 89 | 325.533 | 339.848 | 353.642 | 361.099 | 375.969 | 387.403 | 397.536 | 411.191 |
| 90 | 325.074 | 339.132 | 352.677 | 360.0005 | 374.603 | 385.831 | 395.783 | 409.192 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 91 | 324.623 | 338.428 | 351.73 | 358.921 | 373.262 | 384.288 | 394.061 | 407.229 |
| 92 | 324.18 | 337.737 | 350.799 | 357.8615 | 371.945 | 382.773 | 392.37 | 405.302 |
| 93 | 323.745 | 337.058 | 349.886 | 356.821 | 370.651 | 381.285 | 390.71 | 403.41 |
| 94 | 323.318 | 336.391 | 348.989 | 355.7995 | 369.381 | 379.824 | 389.079 | 401.551 |
| 95 | 322.898 | 335.737 | 348.108 | 354.796 | 368.134 | 378.389 | 387.478 | 399.726 |
| 96 | 322.486 | 335.094 | 347.243 | 353.811 | 366.909 | 376.98 | 385.906 | 397.934 |
| 97 | 322.082 | 334.463 | 346.393 | 352.843 | 365.706 | 375.596 | 384.362 | 396.173 |
| 98 | 321.685 | 333.844 | 345.559 | 351.8935 | 364.525 | 374.237 | 382.845 | 394.445 |
| 99 | 321.295 | 333.235 | 344.74 | 350.9605 | 363.365 | 372.903 | 381.356 | 392.747 |
| 100 | 320.912 | 332.638 | 343.936 | 350.0445 | 362.226 | 371.592 | 379.894 | 391.08 |
| 101 | 320.536 | 332.051 | 343.146 | 349.1445 | 361.108 | 370.306 | 378.458 | 389.444 |
| 102 | 320.167 | 331.475 | 342.371 | 348.2615 | 360.009 | 369.042 | 377.048 | 387.836 |
| 103 | 319.805 | 330.909 | 341.609 | 347.394 | 358.93 | 367.801 | 375.663 | 386.257 |
| 104 | 319.449 | 330.354 | 340.861 | 346.542 | 357.871 | 366.582 | 374.303 | 384.707 |
| 105 | 319.099 | 329.808 | 340.127 | 345.7055 | 356.831 | 365.385 | 372.967 | 383.184 |
| 106 | 318.756 | 329.272 | 339.405 | 344.884 | 355.809 | 364.21 | 371.656 | 381.689 |
| 107 | 318.419 | 328.746 | 338.697 | 344.077 | 354.806 | 363.056 | 370.368 | 380.221 |
| 108 | 318.088 | 328.229 | 338.002 | 343.2845 | 353.821 | 361.923 | 369.103 | 378.779 |
| 109 | 317.763 | 327.722 | 337.318 | 342.507 | 352.854 | 360.81 | 367.861 | 377.363 |
| 110 | 317.443 | 327.224 | 336.648 | 341.743 | 351.904 | 359.717 | 366.641 | 375.973 |
| 111 | 317.13 | 326.734 | 335.989 | 340.9925 | 350.971 | 358.643 | 365.444 | 374.607 |
| 112 | 316.822 | 326.254 | 335.342 | 340.256 | 350.055 | 357.589 | 364.267 | 373.266 |
| 113 | 316.52 | 325.782 | 334.707 | 339.5325 | 349.155 | 356.554 | 363.112 | 371.95 |
| 114 | 316.223 | 325.319 | 334.083 | 338.822 | 348.272 | 355.538 | 361.978 | 370.656 |
| 115 | 315.931 | 324.863 | 333.47 | 338.124 | 347.404 | 354.54 | 360.864 | 369.386 |
| 116 | 315.645 | 324.417 | 332.869 | 337.4385 | 346.552 | 353.559 | 359.77 | 368.139 |
| 117 | 315.363 | 323.978 | 332.278 | 336.7655 | 345.715 | 352.597 | 358.696 | 366.915 |
| 118 | 315.086 | 323.546 | 331.697 | 336.1045 | 344.894 | 351.652 | 357.642 | 365.713 |
| 119 | 314.814 | 323.122 | 331.127 | 335.455 | 344.087 | 350.724 | 356.607 | 364.534 |
| 120 | 314.286 | 322.297 | 330.017 | 334.1915 | 342.517 | 348.918 | 354.592 | 362.238 |
| 121 | 314.029 | 321.896 | 329.478 | 333.577 | 341.753 | 348.04 | 353.612 | 361.12 |
| 122 | 313.777 | 321.502 | 328.948 | 332.974 | 341.003 | 347.177 | 352.649 | 360.023 |
| 123 | 313.529 | 321.116 | 328.428 | 332.381 | 340.266 | 346.33 | 351.704 | 358.946 |
| 124 | 313.286 | 320.737 | 327.917 | 331.7995 | 339.543 | 345.498 | 350.775 | 357.887 |
| 125 | 313.047 | 320.364 | 327.415 | 331.228 | 338.833 | 344.681 | 349.864 | 356.848 |
| 126 | 312.813 | 319.998 | 326.923 | 330.6675 | 338.135 | 343.878 | 348.968 | 355.828 |
| 127 | 312.583 | 319.639 | 326.439 | 330.1165 | 337.451 | 343.09 | 348.089 | 354.825 |
| 128 | 312.357 | 319.286 | 325.965 | 329.5755 | 336.778 | 342.316 | 347.226 | 353.841 |
| 129 | 312.135 | 318.94 | 325.498 | 329.0445 | 336.117 | 341.557 | 346.378 | 352.874 |
| 130 | 311.917 | 318.6 | 325.04 | 328.523 | 335.469 | 340.81 | 345.545 | 351.925 |
| 131 | 311.703 | 318.266 | 324.591 | 328.011 | 334.832 | 340.078 | 344.727 | 350.993 |
| 132 | 311.493 | 317.938 | 324.149 | 327.508 | 334.207 | 339.358 | 343.924 | 350.077 |
| 133 | 311.286 | 317.615 | 323.715 | 327.0135 | 333.592 | 338.651 | 343.136 | 349.178 |
| 134 | 311.083 | 317.299 | 323.289 | 326.529 | 332.989 | 337.957 | 342.361 | 348.296 |
| 135 | 310.884 | 316.988 | 322.871 | 326.0525 | 332.397 | 337.276 | 341.6 | 347.428 |
| 136 | 310.689 | 316.683 | 322.461 | 325.5845 | 331.815 | 336.607 | 340.854 | 346.577 |
| 137 | 310.495 | 316.382 | 322.056 | 325.1245 | 331.244 | 335.95 | 340.121 | 345.743 |
| 138 | 310.306 | 316.087 | 321.66 | 324.673 | 330.684 | 335.306 | 339.402 | 344.923 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 139 | 310.12 | 315.798 | 321.27 | 324.2295 | 330.133 | 334.672 | 338.696 | 344.118 |
| 140 | 309.938 | 315.514 | 320.888 | 323.7945 | 329.592 | 334.05 | 338.002 | 343.327 |
| 141 | 309.76 | 315.235 | 320.513 | 323.367 | 329.061 | 333.44 | 337.321 | 342.551 |
| 142 | 309.585 | 314.961 | 320.145 | 322.948 | 328.54 | 332.84 | 336.652 | 341.788 |
| 143 | 309.412 | 314.693 | 319.783 | 322.536 | 328.028 | 332.251 | 335.995 | 341.039 |
| 144 | 309.243 | 314.429 | 319.428 | 322.1315 | 327.525 | 331.673 | 335.349 | 340.303 |
| 145 | 309.078 | 314.17 | 319.08 | 321.735 | 327.031 | 331.105 | 334.715 | 339.581 |
| 146 | 308.915 | 313.916 | 318.737 | 321.345 | 326.547 | 330.547 | 334.093 | 338.872 |
| 147 | 308.755 | 313.666 | 318.401 | 320.962 | 326.07 | 329.999 | 333.482 | 338.175 |
| 148 | 308.598 | 313.421 | 318.071 | 320.586 | 325.603 | 329.461 | 332.881 | 337.491 |
| 149 | 308.443 | 313.18 | 317.747 | 320.217 | 325.144 | 328.933 | 332.292 | 336.819 |
| 150 | 308.292 | 312.944 | 317.429 | 319.8545 | 324.693 | 328.414 | 331.713 | 336.159 |
| 151 | 308.142 | 312.711 | 317.116 | 319.4985 | 324.25 | 327.905 | 331.145 | 335.511 |
| 152 | 307.995 | 312.482 | 316.808 | 319.148 | 323.816 | 327.406 | 330.588 | 334.876 |
| 153 | 307.851 | 312.257 | 316.506 | 318.8045 | 323.389 | 326.915 | 330.041 | 334.253 |
| 154 | 307.709 | 312.037 | 316.21 | 318.467 | 322.97 | 326.434 | 329.503 | 333.64 |
| 155 | 307.571 | 311.821 | 315.919 | 318.136 | 322.559 | 325.96 | 328.975 | 333.038 |
| 156 | 307.435 | 311.608 | 315.633 | 317.811 | 322.155 | 325.496 | 328.457 | 332.447 |
| 157 | 307.302 | 311.4 | 315.353 | 317.4915 | 321.758 | 325.039 | 327.948 | 331.867 |
| 158 | 307.171 | 311.196 | 315.078 | 317.1785 | 321.368 | 324.591 | 327.447 | 331.297 |
| 159 | 307.042 | 310.995 | 314.808 | 316.8705 | 320.986 | 324.151 | 326.956 | 330.737 |

Table 28 Cooling curve data for B319

| Time | temp (3) | temp (8) | temp (13) | Temp (16) | temp (22) | temp (27) | temp (32) | temp (40) |
|---|---|---|---|---|---|---|---|---|
| 0 | 778 | 778 | 778 | 778 | 778 | 778 | 778 | 778 |
| 1 | 612.39 | 712.876 | 757.368 | 768.0085 | 776.161 | 777.591 | 777.889 | 777.951 |
| 2 | 549.638 | 651.007 | 715.821 | 738.5555 | 764.664 | 773.189 | 776.326 | 777.616 |
| 3 | 514.713 | 609.755 | 679.466 | 707.7895 | 746.653 | 763.429 | 771.572 | 776.328 |
| 4 | 491.493 | 580.212 | 650.15 | 680.8355 | 727.263 | 750.633 | 763.92 | 773.521 |
| 5 | 474.562 | 557.763 | 626.343 | 657.889 | 708.649 | 736.784 | 754.484 | 769.201 |
| 6 | 461.493 | 539.971 | 606.652 | 638.324 | 691.486 | 722.961 | 744.193 | 763.683 |
| 7 | 450.993 | 525.411 | 590.052 | 621.4755 | 675.87 | 709.657 | 733.64 | 757.327 |
| 8 | 442.312 | 513.208 | 575.83 | 606.8105 | 661.713 | 697.078 | 723.174 | 750.432 |
| 9 | 434.975 | 502.788 | 563.48 | 593.921 | 648.871 | 685.289 | 712.991 | 743.222 |
| 10 | 428.665 | 493.751 | 552.623 | 582.4795 | 637.181 | 674.272 | 703.18 | 735.85 |
| 11 | 423.16 | 485.813 | 542.981 | 572.236 | 626.494 | 663.979 | 693.777 | 728.42 |
| 12 | 418.3 | 478.765 | 534.339 | 562.9935 | 616.681 | 654.35 | 684.787 | 721.002 |
| 13 | 413.965 | 472.449 | 526.533 | 554.598 | 607.631 | 645.324 | 676.198 | 713.639 |
| 14 | 410.065 | 466.743 | 519.433 | 546.9225 | 599.245 | 636.842 | 667.988 | 706.362 |
| 15 | 406.53 | 461.549 | 512.928 | 539.8585 | 591.435 | 628.84 | 660.126 | 699.184 |
| 16 | 403.302 | 456.79 | 506.934 | 533.3215 | 584.128 | 621.267 | 652.583 | 692.115 |
| 17 | 400.335 | 452.401 | 501.378 | 527.2395 | 577.262 | 614.077 | 645.334 | 685.162 |
| 18 | 397.591 | 448.332 | 496.201 | 521.553 | 570.784 | 607.228 | 638.352 | 678.326 |
| 19 | 395.04 | 444.538 | 491.354 | 516.212 | 564.649 | 600.685 | 631.616 | 671.609 |
| 20 | 392.657 | 440.984 | 486.794 | 511.173 | 558.817 | 594.416 | 625.104 | 665.009 |
| 21 | 390.419 | 437.639 | 482.487 | 506.4005 | 553.255 | 588.394 | 618.797 | 658.527 |
| 22 | 388.308 | 434.478 | 478.402 | 501.863 | 547.933 | 582.595 | 612.681 | 652.16 |
| 23 | 386.309 | 431.479 | 474.514 | 497.5345 | 542.827 | 576.999 | 606.74 | 645.907 |
| 24 | 384.41 | 428.623 | 470.801 | 493.3925 | 537.914 | 571.586 | 600.962 | 639.766 |
| 25 | 382.598 | 425.894 | 467.245 | 489.417 | 533.178 | 566.343 | 595.336 | 633.734 |
| 26 | 380.864 | 423.28 | 463.828 | 485.592 | 528.601 | 561.255 | 589.851 | 627.811 |
| 27 | 379.2 | 420.767 | 460.538 | 481.9025 | 524.169 | 556.31 | 584.5 | 621.993 |
| 28 | 377.6 | 418.347 | 457.363 | 478.3375 | 519.872 | 551.498 | 579.274 | 616.279 |
| 29 | 376.056 | 416.011 | 454.292 | 474.8845 | 515.697 | 546.811 | 574.168 | 610.668 |
| 30 | 374.565 | 413.75 | 451.316 | 471.5355 | 511.637 | 542.24 | 569.174 | 605.156 |
| 31 | 373.108 | 411.553 | 448.429 | 468.285 | 507.688 | 537.784 | 564.293 | 599.744 |
| 32 | 371.704 | 409.423 | 445.621 | 465.1195 | 503.836 | 533.429 | 559.513 | 594.429 |
| 33 | 370.341 | 407.354 | 442.888 | 462.0375 | 500.076 | 529.17 | 554.831 | 589.207 |
| 34 | 369.016 | 405.341 | 440.226 | 459.0315 | 496.404 | 525.004 | 550.244 | 584.079 |
| 35 | 367.726 | 403.379 | 437.63 | 456.0985 | 492.815 | 520.928 | 545.748 | 579.042 |
| 36 | 366.468 | 401.466 | 435.095 | 453.234 | 489.305 | 516.936 | 541.341 | 574.095 |
| 37 | 365.242 | 399.599 | 432.62 | 450.4345 | 485.87 | 513.025 | 537.019 | 569.235 |
| 38 | 364.044 | 397.775 | 430.2 | 447.696 | 482.508 | 509.193 | 532.78 | 564.462 |
| 39 | 362.874 | 395.991 | 427.833 | 445.017 | 479.215 | 505.437 | 528.621 | 559.773 |
| 40 | 361.729 | 394.247 | 425.517 | 442.3945 | 475.988 | 501.755 | 524.54 | 555.167 |
| 41 | 360.609 | 392.54 | 423.248 | 439.825 | 472.826 | 498.143 | 520.536 | 550.643 |
| 42 | 359.513 | 390.868 | 421.027 | 437.3085 | 469.726 | 494.601 | 516.607 | 546.2 |
| 43 | 358.438 | 389.23 | 418.85 | 434.842 | 466.687 | 491.126 | 512.75 | 541.835 |
| 44 | 357.385 | 387.625 | 416.716 | 432.424 | 463.706 | 487.717 | 508.965 | 537.549 |
| 45 | 356.354 | 386.052 | 414.624 | 430.0525 | 460.782 | 484.371 | 505.248 | 533.338 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 46 | 355.343 | 384.509 | 412.572 | 427.727 | 457.912 | 481.087 | 501.599 | 529.202 |
| 47 | 354.352 | 382.997 | 410.559 | 425.4455 | 455.097 | 477.863 | 498.017 | 525.139 |
| 48 | 353.38 | 381.513 | 408.585 | 423.2065 | 452.333 | 474.699 | 494.499 | 521.149 |
| 49 | 352.426 | 380.058 | 406.648 | 421.01 | 449.621 | 471.592 | 491.045 | 517.229 |
| 50 | 351.49 | 378.63 | 404.747 | 418.854 | 446.959 | 468.542 | 487.652 | 513.378 |
| 51 | 350.569 | 377.228 | 402.881 | 416.738 | 444.345 | 465.548 | 484.322 | 509.596 |
| 52 | 349.666 | 375.851 | 401.05 | 414.661 | 441.78 | 462.608 | 481.052 | 505.882 |
| 53 | 348.781 | 374.5 | 399.252 | 412.622 | 439.261 | 459.721 | 477.84 | 502.234 |
| 54 | 347.913 | 373.174 | 397.487 | 410.62 | 436.787 | 456.886 | 474.686 | 498.65 |
| 55 | 347.061 | 371.873 | 395.754 | 408.654 | 434.358 | 454.102 | 471.587 | 495.13 |
| 56 | 346.224 | 370.596 | 394.053 | 406.724 | 431.973 | 451.368 | 468.544 | 491.672 |
| 57 | 345.402 | 369.341 | 392.382 | 404.829 | 429.631 | 448.683 | 465.556 | 488.276 |
| 58 | 344.596 | 368.109 | 390.741 | 402.968 | 427.33 | 446.046 | 462.621 | 484.941 |
| 59 | 343.803 | 366.9 | 389.13 | 401.14 | 425.072 | 443.456 | 459.739 | 481.664 |
| 60 | 343.026 | 365.712 | 387.548 | 399.345 | 422.853 | 440.912 | 456.907 | 478.446 |
| 61 | 342.26 | 364.545 | 385.995 | 397.583 | 420.674 | 438.414 | 454.127 | 475.285 |
| 62 | 341.51 | 363.399 | 384.469 | 395.852 | 418.535 | 435.961 | 451.395 | 472.18 |
| 63 | 340.773 | 362.274 | 382.971 | 394.152 | 416.433 | 433.551 | 448.713 | 469.13 |
| 64 | 340.049 | 361.17 | 381.499 | 392.4825 | 414.369 | 431.184 | 446.078 | 466.134 |
| 65 | 339.339 | 360.085 | 380.054 | 390.843 | 412.342 | 428.859 | 443.489 | 463.191 |
| 66 | 338.641 | 359.02 | 378.635 | 389.232 | 410.351 | 426.576 | 440.947 | 460.301 |
| 67 | 337.956 | 357.973 | 377.241 | 387.6505 | 408.395 | 424.333 | 438.45 | 457.461 |
| 68 | 337.283 | 356.945 | 375.872 | 386.097 | 406.474 | 422.13 | 435.997 | 454.672 |
| 69 | 336.623 | 355.936 | 374.527 | 384.571 | 404.587 | 419.966 | 433.587 | 451.932 |
| 70 | 335.973 | 354.945 | 373.206 | 383.072 | 402.734 | 417.84 | 431.221 | 449.241 |
| 71 | 335.336 | 353.971 | 371.909 | 381.6 | 400.914 | 415.752 | 428.896 | 446.597 |
| 72 | 334.71 | 353.014 | 370.635 | 380.1545 | 399.126 | 413.702 | 426.612 | 444 |
| 73 | 334.095 | 352.075 | 369.383 | 378.734 | 397.369 | 411.687 | 424.369 | 441.449 |
| 74 | 333.49 | 351.152 | 368.154 | 377.339 | 395.644 | 409.708 | 422.166 | 438.944 |
| 75 | 332.897 | 350.246 | 366.946 | 375.969 | 393.95 | 407.765 | 420.002 | 436.482 |
| 76 | 332.314 | 349.356 | 365.76 | 374.6225 | 392.285 | 405.856 | 417.876 | 434.065 |
| 77 | 331.742 | 348.481 | 364.595 | 373.3005 | 390.65 | 403.98 | 415.788 | 431.69 |
| 78 | 331.179 | 347.622 | 363.45 | 372.0015 | 389.044 | 402.138 | 413.737 | 429.357 |
| 79 | 330.627 | 346.779 | 362.326 | 370.726 | 387.467 | 400.329 | 411.722 | 427.066 |
| 80 | 330.084 | 345.95 | 361.222 | 369.4735 | 385.917 | 398.551 | 409.743 | 424.815 |
| 81 | 329.551 | 345.136 | 360.137 | 368.2425 | 384.395 | 396.806 | 407.799 | 422.604 |
| 82 | 329.028 | 344.336 | 359.072 | 367.034 | 382.9 | 395.091 | 405.889 | 420.432 |
| 83 | 328.513 | 343.551 | 358.026 | 365.846 | 381.432 | 393.406 | 404.013 | 418.299 |
| 84 | 328.008 | 342.779 | 356.998 | 364.6795 | 379.989 | 391.752 | 402.171 | 416.203 |
| 85 | 327.512 | 342.021 | 355.988 | 363.5335 | 378.572 | 390.126 | 400.361 | 414.145 |
| 86 | 327.025 | 341.277 | 354.996 | 362.408 | 377.18 | 388.53 | 398.583 | 412.123 |
| 87 | 326.546 | 340.545 | 354.022 | 361.3025 | 375.813 | 386.962 | 396.837 | 410.137 |
| 88 | 326.075 | 339.827 | 353.064 | 360.2165 | 374.47 | 385.421 | 395.122 | 408.187 |
| 89 | 325.613 | 339.121 | 352.124 | 359.1495 | 373.151 | 383.909 | 393.438 | 406.272 |
| 90 | 325.159 | 338.428 | 351.201 | 358.102 | 371.855 | 382.423 | 391.783 | 404.39 |
| 91 | 324.713 | 337.747 | 350.294 | 357.0725 | 370.582 | 380.963 | 390.158 | 402.541 |
| 92 | 324.275 | 337.078 | 349.403 | 356.0615 | 369.332 | 379.529 | 388.561 | 400.726 |
| 93 | 323.845 | 336.421 | 348.528 | 355.0685 | 368.104 | 378.121 | 386.993 | 398.942 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 94 | 323.423 | 335.776 | 347.668 | 354.093 | 366.898 | 376.737 | 385.452 | 397.19 |
| 95 | 323.008 | 335.143 | 346.824 | 353.135 | 365.713 | 375.378 | 383.939 | 395.469 |
| 96 | 322.601 | 334.52 | 345.995 | 352.1945 | 364.55 | 374.043 | 382.453 | 393.779 |
| 97 | 322.2 | 333.909 | 345.18 | 351.2695 | 363.407 | 372.732 | 380.993 | 392.118 |
| 98 | 321.807 | 333.308 | 344.38 | 350.3615 | 362.284 | 371.444 | 379.558 | 390.487 |
| 99 | 321.421 | 332.718 | 343.594 | 349.47 | 361.181 | 370.179 | 378.15 | 388.885 |
| 100 | 321.041 | 332.139 | 342.822 | 348.594 | 360.097 | 368.936 | 376.766 | 387.311 |
| 101 | 320.669 | 331.57 | 342.064 | 347.7335 | 359.033 | 367.715 | 375.406 | 385.765 |
| 102 | 320.303 | 331.011 | 341.319 | 346.888 | 357.988 | 366.516 | 374.071 | 384.246 |
| 103 | 319.943 | 330.461 | 340.587 | 346.0575 | 356.961 | 365.338 | 372.759 | 382.754 |
| 104 | 319.59 | 329.922 | 339.868 | 345.242 | 355.952 | 364.181 | 371.471 | 381.289 |
| 105 | 319.243 | 329.392 | 339.162 | 344.441 | 354.961 | 363.045 | 370.206 | 379.849 |
| 106 | 318.902 | 328.872 | 338.469 | 343.6535 | 353.988 | 361.928 | 368.962 | 378.435 |
| 107 | 318.568 | 328.36 | 337.787 | 342.8805 | 353.032 | 360.832 | 367.741 | 377.047 |
| 108 | 318.239 | 327.858 | 337.118 | 342.1215 | 352.093 | 359.755 | 366.542 | 375.682 |
| 109 | 317.916 | 327.365 | 336.461 | 341.376 | 351.17 | 358.697 | 365.363 | 374.342 |
| 110 | 317.599 | 326.88 | 335.815 | 340.6425 | 350.264 | 357.657 | 364.206 | 373.026 |
| 111 | 317.287 | 326.404 | 335.181 | 339.923 | 349.374 | 356.636 | 363.069 | 371.733 |
| 112 | 316.981 | 325.937 | 334.558 | 339.216 | 348.5 | 355.633 | 361.952 | 370.462 |
| 113 | 316.68 | 325.478 | 333.946 | 338.522 | 347.641 | 354.648 | 360.855 | 369.215 |
| 114 | 316.385 | 325.026 | 333.345 | 337.84 | 346.798 | 353.681 | 359.778 | 367.989 |
| 115 | 316.093 | 324.582 | 332.754 | 337.1695 | 345.969 | 352.731 | 358.72 | 366.787 |
| 116 | 315.808 | 324.146 | 332.173 | 336.51 | 345.155 | 351.798 | 357.682 | 365.606 |
| 117 | 315.527 | 323.718 | 331.603 | 335.8635 | 344.356 | 350.881 | 356.661 | 364.446 |
| 118 | 315.252 | 323.297 | 331.043 | 335.2285 | 343.571 | 349.98 | 355.659 | 363.306 |
| 119 | 314.982 | 322.885 | 330.493 | 334.6045 | 342.799 | 349.096 | 354.674 | 362.186 |
| 120 | 314.716 | 322.479 | 329.953 | 333.992 | 342.042 | 348.227 | 353.707 | 361.086 |
| 121 | 314.456 | 322.081 | 329.423 | 333.3905 | 341.298 | 347.374 | 352.757 | 360.006 |
| 122 | 314.2 | 321.69 | 328.902 | 332.7995 | 340.567 | 346.536 | 351.823 | 358.945 |
| 123 | 313.949 | 321.306 | 328.391 | 332.219 | 339.849 | 345.712 | 350.907 | 357.902 |
| 124 | 313.702 | 320.929 | 327.888 | 331.649 | 339.144 | 344.904 | 350.006 | 356.878 |
| 125 | 313.459 | 320.559 | 327.395 | 331.0885 | 338.451 | 344.109 | 349.121 | 355.872 |
| 126 | 313.221 | 320.195 | 326.91 | 330.5385 | 337.771 | 343.329 | 348.252 | 354.884 |
| 127 | 312.987 | 319.838 | 326.434 | 329.9985 | 337.103 | 342.562 | 347.399 | 353.913 |
| 128 | 312.757 | 319.487 | 325.966 | 329.4675 | 336.446 | 341.809 | 346.56 | 352.959 |
| 129 | 312.531 | 319.142 | 325.507 | 328.946 | 335.802 | 341.07 | 345.737 | 352.022 |
| 130 | 312.31 | 318.803 | 325.056 | 328.434 | 335.168 | 340.343 | 344.928 | 351.102 |
| 131 | 312.092 | 318.471 | 324.612 | 327.931 | 334.546 | 339.63 | 344.133 | 350.198 |
| 132 | 311.878 | 318.144 | 324.177 | 327.437 | 333.935 | 338.929 | 343.352 | 349.31 |
| 133 | 311.668 | 317.823 | 323.749 | 326.9515 | 333.335 | 338.24 | 342.585 | 348.438 |
| 134 | 311.461 | 317.507 | 323.329 | 326.4745 | 332.745 | 337.564 | 341.832 | 347.582 |
| 135 | 311.257 | 317.196 | 322.915 | 326.0055 | 332.166 | 336.9 | 341.094 | 346.742 |
| 136 | 311.057 | 316.891 | 322.509 | 325.545 | 331.597 | 336.248 | 340.368 | 345.917 |
| 137 | 310.861 | 316.591 | 322.11 | 325.093 | 331.039 | 335.608 | 339.655 | 345.106 |
| 138 | 310.668 | 316.298 | 321.719 | 324.649 | 330.49 | 334.978 | 338.955 | 344.31 |
| 139 | 310.479 | 316.009 | 321.335 | 324.2135 | 329.951 | 334.36 | 338.266 | 343.527 |
| 140 | 310.294 | 315.726 | 320.958 | 323.785 | 329.421 | 333.753 | 337.59 | 342.759 |
| 141 | 310.112 | 315.448 | 320.587 | 323.3645 | 328.901 | 333.157 | 336.926 | 342.003 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 142 | 309.933 | 315.175 | 320.223 | 322.9515 | 328.391 | 332.571 | 336.274 | 341.262 |
| 143 | 309.757 | 314.906 | 319.865 | 322.546 | 327.889 | 331.995 | 335.633 | 340.533 |
| 144 | 309.585 | 314.643 | 319.514 | 322.147 | 327.396 | 331.43 | 335.004 | 339.817 |
| 145 | 309.415 | 314.384 | 319.169 | 321.756 | 326.912 | 330.875 | 334.386 | 339.114 |
| 146 | 309.249 | 314.13 | 318.831 | 321.3715 | 326.437 | 330.329 | 333.778 | 338.423 |
| 147 | 309.085 | 313.88 | 318.498 | 320.994 | 325.969 | 329.794 | 333.182 | 337.745 |
| 148 | 308.925 | 313.635 | 318.171 | 320.623 | 325.511 | 329.267 | 332.595 | 337.078 |
| 149 | 308.767 | 313.393 | 317.85 | 320.2585 | 325.06 | 328.751 | 332.02 | 336.424 |
| 150 | 308.61 | 313.155 | 317.534 | 319.9 | 324.618 | 328.244 | 331.456 | 335.782 |
| 151 | 308.457 | 312.922 | 317.223 | 319.548 | 324.183 | 327.746 | 330.901 | 335.151 |
| 152 | 308.307 | 312.693 | 316.918 | 319.2025 | 323.756 | 327.256 | 330.357 | 334.532 |
| 153 | 308.16 | 312.468 | 316.619 | 318.863 | 323.337 | 326.775 | 329.821 | 333.924 |
| 154 | 308.016 | 312.248 | 316.326 | 318.53 | 322.925 | 326.303 | 329.296 | 333.326 |
| 155 | 307.874 | 312.031 | 316.037 | 318.203 | 322.521 | 325.839 | 328.779 | 332.738 |
| 156 | 307.735 | 311.819 | 315.754 | 317.8815 | 322.123 | 325.383 | 328.272 | 332.161 |
| 157 | 307.598 | 311.61 | 315.476 | 317.5655 | 321.733 | 324.936 | 327.773 | 331.595 |
| 158 | 307.464 | 311.405 | 315.203 | 317.256 | 321.349 | 324.496 | 327.283 | 331.038 |
| 159 | 307.332 | 311.204 | 314.935 | 316.9515 | 320.973 | 324.064 | 326.802 | 330.491 |
| 160 | 307.203 | 311.006 | 314.671 | 316.6525 | 320.603 | 323.64 | 326.33 | 329.953 |

# APPENDIX D

# EXAMPLE OF MATLAB CODE

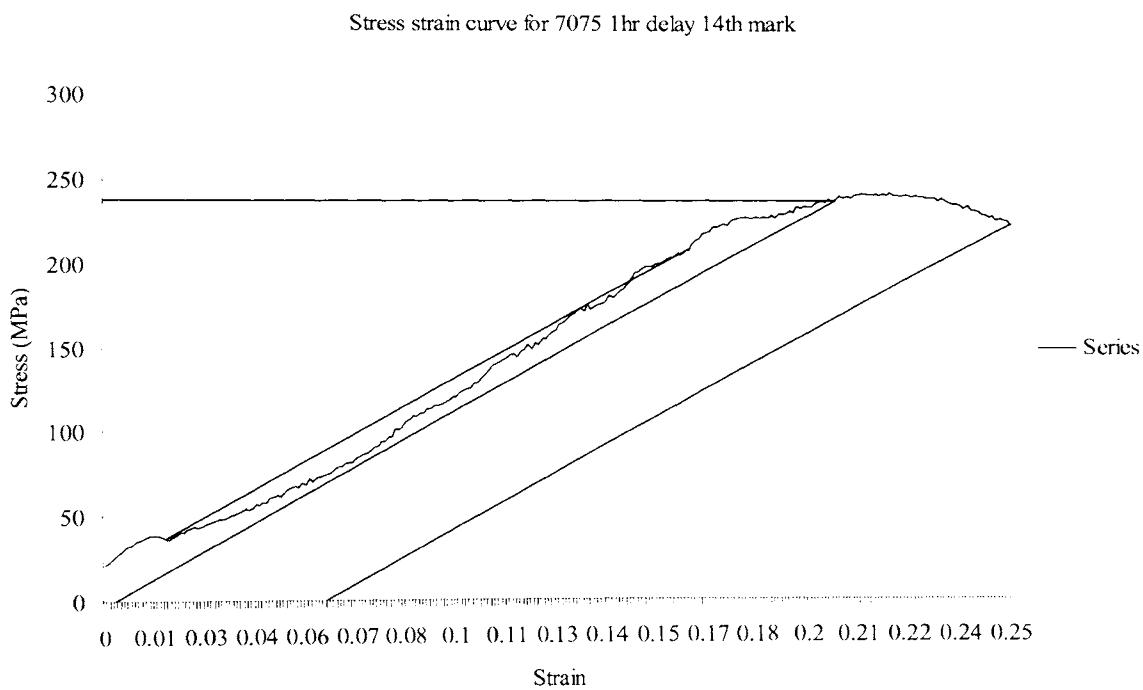
EXAMPLE OF MATLAB CODE USED TO SOLVE FOR CRITICAL TIMES

```
syms  x1 x2 x3 x4 x5 x6 x7 x8

eq1='3.05 = 0.1599/x1 + 0.16/x2 + 0.2346/x3 + 0.3278/x4 + 0.3332/x5 + 0.503/x6 +
0.797/x7 + 1.1621/x8'

eq2='23.5 = 0.4447/x1 + 0.4678/x2 + 0.5371/x3 + 0.8201/x4 + 1.0568/x5 + 1.4092/x6 +
1.952/x7 + 3.1013/x8'

eq3= '64.5 = .844/x1 +
.9108/x2+1.249/x3+1.4993/x4+1.9658/x5+2.7876/x6+3.6317/x7+5.2644/x8'

eq4= '99.4= .9996/x1 +
1.2261/x2+1.6792/x3+2.0258/x4+2.6388/x5+3.6117/x6+4.6379/x7+6.2773/x8'

eq5= '192.2=1.9192/x1 +
2.0968/x2+2.4878/x3+3.2519/x4+4.0693/x5+4.9222/x6+6.1484/x7+7.1968/x8'

eq6= '295.1=2.7122/x1 +
2.4922/x2+3.4451/x3+4.056/x4+4.8378/x5+5.7663/x6+6.2251/x7+7.4522/x8'

eq7= '420.2=3.7086/x1 +
3.5918/x2+3.9826/x3+4.6913/x4+5.131/x5+5.7175/x6+6.4749/x7+7.6721/x8'

eq8= '668.4=3.2741/x1 +
4.398/x2+4.3492/x3+4.6668/x4+5.5709/x5+5.693/x6+6.4993/x7+7.55/x8 '



[x1 x2 x3 x4 x5 x6 x7 x8]=solve(eq1,eq2,eq3,eq4,eq5,eq6,eq7,eq8,x1, x2, x3, x4, x5, x6,
x7, x8)
```

# APPENDIX E

# EXAMPLE OF STRESS STRAIN CURVE

Example of Stress Strain Curve Plotted



# APPENDIX F

# THERMOCOUPLE COOLING DATA FOR A356

Thermocouple cooling data for A356

| Time (s) | k7(Deg C) | k2(Deg C) | k3(Deg C) | k4(Deg C) | k5(Deg C) | k6(Deg C) |
|---|---|---|---|---|---|---|
| 00:00.6 | 437.891 | 537.8 | 412.968 | 506.829 | 537.527 | 444.666 |
| 00:01.2 | 437.895 | 537.781 | 412.945 | 506.785 | 537.506 | 444.563 |
| 00:01.9 | 437.879 | 537.814 | 412.907 | 506.775 | 537.505 | 444.675 |
| 00:02.5 | 437.995 | 537.755 | 412.88 | 506.845 | 537.555 | 444.672 |
| 00:03.1 | 437.844 | 537.797 | 412.838 | 506.833 | 537.501 | 444.61 |
| 00:03.7 | 437.856 | 537.812 | 412.908 | 506.813 | 537.473 | 444.631 |
| 00:04.3 | 437.916 | 537.762 | 412.896 | 506.82 | 537.517 | 444.666 |
| 00:05.0 | 437.951 | 537.746 | 412.863 | 506.803 | 537.485 | 444.601 |
| 00:05.6 | 437.912 | 537.77 | 412.889 | 506.789 | 537.479 | 444.637 |
| 00:06.2 | 437.907 | 537.826 | 412.901 | 506.78 | 537.479 | 444.766 |
| 00:06.8 | 437.847 | 537.763 | 412.873 | 506.812 | 537.52 | 444.629 |
| 00:07.4 | 437.879 | 537.774 | 412.843 | 506.763 | 537.52 | 444.631 |
| 00:08.1 | 437.874 | 537.725 | 412.866 | 506.773 | 537.484 | 444.651 |
| 00:08.7 | 437.879 | 537.751 | 412.848 | 506.754 | 537.491 | 444.64 |
| 00:09.3 | 437.839 | 537.723 | 412.894 | 506.78 | 537.503 | 444.651 |
| 00:09.9 | 437.846 | 537.72 | 412.884 | 506.806 | 537.468 | 444.67 |
| 00:10.5 | 437.89 | 537.774 | 412.863 | 506.799 | 537.456 | 444.622 |
| 00:11.1 | 437.823 | 537.777 | 412.91 | 506.792 | 537.482 | 444.596 |
| 00:11.8 | 437.888 | 537.767 | 412.88 | 506.826 | 537.494 | 444.575 |
| 00:12.4 | 437.865 | 537.732 | 412.813 | 506.78 | 537.475 | 444.605 |
| 00:13.0 | 437.868 | 537.753 | 412.894 | 506.717 | 537.48 | 444.614 |
| 00:13.6 | 437.877 | 537.732 | 412.831 | 506.82 | 537.391 | 444.591 |
| 00:14.2 | 437.849 | 537.755 | 412.815 | 506.777 | 537.479 | 444.607 |
| 00:14.9 | 437.851 | 537.742 | 412.81 | 506.845 | 537.475 | 444.652 |
| 00:15.5 | 437.839 | 537.786 | 412.87 | 506.796 | 537.471 | 444.587 |
| 00:16.1 | 437.863 | 537.8 | 412.824 | 506.845 | 537.461 | 444.614 |
| 00:16.7 | 437.847 | 537.739 | 412.845 | 506.798 | 537.468 | 444.638 |
| 00:17.3 | 437.849 | 537.713 | 412.905 | 506.756 | 537.458 | 444.626 |
| 00:18.0 | 437.893 | 537.729 | 412.836 | 506.812 | 537.456 | 444.591 |
| 00:18.6 | 437.812 | 537.758 | 412.924 | 506.791 | 537.41 | 444.549 |
| 00:19.2 | 437.816 | 537.704 | 412.852 | 506.812 | 537.484 | 444.565 |
| 00:19.8 | 437.87 | 537.711 | 412.885 | 506.761 | 537.482 | 444.621 |
| 00:20.4 | 437.832 | 537.709 | 412.838 | 506.813 | 537.465 | 444.631 |
| 00:21.1 | 437.851 | 537.694 | 412.861 | 506.833 | 537.417 | 444.642 |
| 00:21.7 | 437.828 | 537.741 | 412.843 | 506.752 | 537.43 | 444.61 |
| 00:22.3 | 437.851 | 537.748 | 412.787 | 506.728 | 537.412 | 444.594 |
| 00:22.9 | 437.9 | 537.706 | 412.868 | 506.78 | 537.381 | 444.605 |
| 00:23.5 | 437.854 | 537.762 | 412.847 | 506.773 | 537.402 | 444.603 |
| 00:24.2 | 437.825 | 537.756 | 412.799 | 506.813 | 537.487 | 444.579 |
| 00:24.8 | 437.828 | 537.774 | 412.894 | 506.764 | 537.33 | 444.61 |
| 00:25.4 | 437.823 | 537.68 | 412.834 | 506.773 | 537.444 | 444.558 |
| 00:26.0 | 437.811 | 537.737 | 412.848 | 506.761 | 537.395 | 444.598 |
| 00:26.6 | 437.846 | 537.716 | 412.824 | 506.796 | 537.444 | 444.621 |
| 00:27.2 | 437.805 | 537.708 | 412.81 | 506.784 | 537.403 | 444.596 |
| 00:27.9 | 437.846 | 537.742 | 412.801 | 506.761 | 537.494 | 444.621 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 00:28.5 | 437.861 | 537.735 | 412.764 | 506.752 | 537.414 | 444.58 |
| 00:29.1 | 437.874 | 537.769 | 412.817 | 506.78 | 537.477 | 444.598 |
| 00:29.7 | 437.812 | 537.721 | 412.922 | 506.647 | 537.505 | 444.558 |
| 00:30.3 | 437.777 | 537.758 | 412.841 | 506.773 | 537.445 | 444.594 |
| 00:31.0 | 437.868 | 537.758 | 412.752 | 506.754 | 537.421 | 444.615 |
| 00:31.6 | 437.783 | 537.676 | 412.843 | 506.735 | 537.381 | 444.528 |
| 00:32.2 | 437.837 | 537.765 | 412.813 | 506.764 | 537.449 | 444.596 |
| 00:32.8 | 437.8 | 537.748 | 412.827 | 506.731 | 537.417 | 444.587 |
| 00:33.4 | 437.849 | 537.716 | 412.813 | 506.731 | 537.409 | 444.558 |
| 00:34.1 | 437.809 | 537.742 | 412.787 | 506.796 | 537.382 | 444.559 |
| 00:34.7 | 437.872 | 537.702 | 412.836 | 506.785 | 537.347 | 444.615 |
| 00:35.3 | 437.828 | 537.748 | 412.82 | 506.761 | 537.452 | 444.528 |
| 00:35.9 | 437.818 | 537.721 | 412.79 | 506.738 | 537.417 | 444.524 |
| 00:36.5 | 437.847 | 537.737 | 412.824 | 506.743 | 537.389 | 444.607 |
| 00:37.2 | 437.753 | 537.695 | 412.769 | 506.789 | 537.405 | 444.61 |
| 00:37.8 | 437.835 | 537.692 | 412.773 | 506.735 | 537.454 | 444.551 |
| 00:38.4 | 437.79 | 537.734 | 412.829 | 506.742 | 537.416 | 444.777 |
| 00:39.0 | 437.774 | 537.716 | 400.765 | 420.773 | 537.396 | 475.207 |
| 00:39.6 | 432.762 | 537.66 | 395.197 | 420.891 | 537.4 | 476.685 |
| 00:40.3 | 432.825 | 537.704 | 397.183 | 421.241 | 537.414 | 477.883 |
| 00:40.9 | 433.004 | 537.645 | 395.845 | 423.057 | 437.47 | 440.207 |
| 00:41.5 | 430.846 | 537.671 | 392.809 | 463.638 | 537.307 | 537.069 |
| 00:42.1 | 535.028 | 537.676 | 537.687 | 537.485 | 537.438 | 537.001 |
| 00:42.7 | 534.732 | 537.681 | 537.569 | 537.29 | 537.358 | 536.926 |
| 00:43.4 | 534.342 | 537.512 | 537.277 | 536.945 | 537.131 | 536.692 |
| 00:44.0 | 533.942 | 536.975 | 536.809 | 536.333 | 536.737 | 536.313 |
| 00:44.6 | 533.466 | 536.111 | 536.083 | 535.66 | 536.353 | 536.054 |
| 00:45.2 | 532.788 | 535.108 | 534.624 | 534.814 | 535.667 | 535.601 |
| 00:45.8 | 531.58 | 533.62 | 533.482 | 533.711 | 534.809 | 534.942 |
| 00:46.4 | 530.606 | 532.068 | 532.307 | 532.643 | 533.881 | 534.134 |
| 00:47.1 | 529.656 | 530.621 | 531.176 | 531.095 | 532.847 | 533.398 |
| 00:47.7 | 528.588 | 529.016 | 530.191 | 529.425 | 531.73 | 532.597 |
| 00:48.3 | 527.76 | 527.409 | 529.334 | 526.001 | 530.651 | 531.905 |
| 00:48.9 | 526.82 | 525.847 | 528.311 | 525.025 | 529.62 | 531.116 |
| 00:49.5 | 526.134 | 524.56 | 527.465 | 525.119 | 528.596 | 530.398 |
| 00:50.2 | 525.322 | 523.461 | 526.748 | 524.876 | 527.678 | 529.618 |
| 00:50.8 | 524.616 | 522.289 | 526.029 | 523.841 | 526.72 | 528.869 |
| 00:51.4 | 523.776 | 521.26 | 525.38 | 523.085 | 525.749 | 528.124 |
| 00:52.0 | 523.053 | 520.149 | 524.733 | 522.534 | 524.743 | 527.383 |
| 00:52.6 | 522.093 | 519.034 | 523.755 | 522.431 | 523.886 | 526.723 |
| 00:53.3 | 521.328 | 517.757 | 523.09 | 521.813 | 522.982 | 525.861 |
| 00:53.9 | 520.588 | 516.43 | 521.995 | 520.891 | 522.2 | 525.137 |
| 00:54.5 | 519.808 | 515.11 | 520.859 | 520.163 | 521.344 | 524.458 |
| 00:55.1 | 519.06 | 514.084 | 520.165 | 519.428 | 520.546 | 523.674 |
| 00:55.7 | 518.367 | 513.056 | 519.122 | 519.442 | 519.704 | 522.943 |
| 00:56.4 | 517.701 | 512.259 | 518.049 | 519.967 | 518.875 | 522.228 |
| 00:57.0 | 517.013 | 511.634 | 517.429 | 519.582 | 518.117 | 521.556 |
| 00:57.6 | 516.253 | 511.069 | 517.067 | 519.54 | 517.244 | 520.947 |

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|---|---|---|---|---|---|---|
| 00:58.2 | 515.546 | 510.583 | 516.54 | 519.076 | 516.51 | 520.263 |
| 00:58.8 | 514.741 | 509.953 | 515.966 | 518.507 | 515.705 | 519.545 |
| 00:59.5 | 514.026 | 509.354 | 515.392 | 517.762 | 514.87 | 518.752 |
| 01:00.1 | 513.117 | 508.765 | 514.769 | 517.13 | 514.087 | 517.97 |
| 01:00.7 | 505.928 | 508.248 | 514.087 | 516.293 | 512.083 | 515.39 |
| 01:01.3 | 434.15 | 507.647 | 514.534 | 515.129 | 422.909 | 503.617 |
| 01:01.9 | 149.238 | 508.148 | 510.231 | 396.775 | 98.3011 | 255.152 |
| 01:02.6 | 109.097 | 507.376 | 509.045 | 289.305 | 98.0635 | 221.273 |
| 01:03.2 | 102.754 | 505.545 | 508.643 | 301.695 | 97.6477 | 167.374 |
| 01:03.8 | 98.8125 | 502.77 | 507.726 | 306.942 | 97.8439 | 168.228 |
| 01:04.4 | 97.7665 | 499.311 | 506.552 | 304.203 | 97.8691 | 149.702 |
| 01:05.0 | 98.8197 | 494.923 | 505.061 | 300.391 | 97.3814 | 136.412 |
| 01:05.6 | 97.3094 | 489.922 | 503.177 | 296.489 | 97.5038 | 131.16 |
| 01:06.3 | 96.0069 | 484.007 | 500.883 | 287.863 | 97.2968 | 128.912 |
| 01:06.9 | 97.7035 | 477.359 | 498.06 | 280.824 | 96.6868 | 127.643 |
| 01:07.5 | 97.16 | 469.985 | 494.994 | 274.031 | 96.5933 | 124.842 |
| 01:08.1 | 96.104 | 461.904 | 491.359 | 266.664 | 96.2263 | 122.227 |
| 01:08.7 | 95.4926 | 453.267 | 487.488 | 260.712 | 95.676 | 120.639 |
| 01:09.4 | 95.9404 | 444.203 | 483.284 | 250.393 | 95.649 | 119.987 |
| 01:10.0 | 93.4076 | 434.896 | 478.828 | 244.823 | 95.7767 | 117.077 |
| 01:10.6 | 89.3017 | 425.603 | 474.037 | 235.437 | 95.8289 | 114.798 |
| 01:11.2 | 86.1151 | 416.216 | 469.016 | 226.123 | 95.8217 | 112.573 |
| 01:11.8 | 83.5508 | 406.815 | 463.577 | 103.249 | 95.7623 | 110.354 |
| 01:12.5 | 76.5443 | 397.391 | 457.892 | 100.769 | 95.7623 | 107.585 |
| 01:13.1 | 74.7811 | 380.712 | 452.076 | 103.547 | 95.6346 | 106.295 |
| 01:13.7 | 72.9606 | 339.361 | 446.107 | 102.522 | 95.8882 | 106.661 |
| 01:14.3 | 72.5937 | 299.15 | 439.86 | 103.108 | 95.6203 | 104.532 |
| 01:14.9 | 41.0142 | 274.17 | 433.487 | 102.237 | 95.2445 | 104.093 |
| 01:15.6 | 51.8798 | 259.118 | 427.209 | 101.351 | 95.5052 | 106.05 |
| 01:16.2 | 62.6952 | 241.876 | 421.023 | 101.517 | 95.6328 | 106.167 |
| 01:16.8 | 66.383 | 222.086 | 414.985 | 102.175 | 95.7821 | 111.42 |
| 01:17.4 | 68.2855 | 206.988 | 409.028 | 104.498 | 95.7407 | 124.329 |
| 01:18.0 | 69.8204 | 198.429 | 403.357 | 105.462 | 95.6616 | 133.609 |
| 01:18.7 | 71.4049 | 194.16 | 398.066 | 106.019 | 95.721 | 137.258 |
| 01:19.3 | 72.5024 | 192.089 | 392.871 | 104.056 | 95.7138 | 115.168 |
| 01:19.9 | 70.6315 | 191.321 | 388.062 | 105.972 | 95.5681 | 105.417 |
| 01:20.5 | 68.6276 | 191.054 | 383.487 | 104.763 | 95.6221 | 106.315 |
| 01:21.1 | 67.7249 | 187.807 | 378.834 | 104.29 | 95.5897 | 111.742 |
| 01:21.8 | 67.8915 | 181.388 | 374.258 | 104.4 | 95.6023 | 121.044 |
| 01:22.4 | 68.1458 | 174.91 | 369.794 | 104.749 | 95.6346 | 128.489 |
| 01:23.0 | 68.6455 | 170.59 | 365.421 | 105.116 | 95.6454 | 132.41 |
| 01:23.6 | 69.6431 | 165.665 | 361.313 | 105.602 | 95.649 | 133.8 |
| 01:24.2 | 69.8311 | 163.108 | 357.302 | 105.724 | 95.6472 | 135.313 |
| 01:24.8 | 70.6852 | 161.958 | 353.479 | 106.138 | 95.6221 | 135.778 |
| 01:25.5 | 70.7998 | 159.417 | 349.75 | 106.426 | 95.6688 | 135.984 |
| 01:26.1 | 70.9842 | 156.542 | 346.225 | 106.209 | 95.6364 | 136.113 |
| 01:26.7 | 71.097 | 155.872 | 342.734 | 106.227 | 95.6958 | 136.127 |
| 01:27.3 | 71.1543 | 155.405 | 339.373 | 106.268 | 95.6382 | 136.111 |

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| 01:27.9 | 72.0119 | 154.923 | 336.094 | 106.436 | 95.6526 | 136.227 |
| 01:28.6 | 72.0441 | 154.28 | 332.818 | 106.552 | 95.6346 | 135.938 |
| 01:29.2 | 72.0387 | 152.742 | 329.733 | 106.314 | 95.5879 | 135.563 |
| 01:29.8 | 71.3208 | 150.622 | 326.673 | 106.202 | 95.5843 | 135.168 |
| 01:30.4 | 71.5858 | 149.517 | 323.651 | 102.855 | 95.5645 | 134.769 |
| 01:31.0 | 71.2241 | 147.134 | 320.641 | 102.866 | 95.5681 | 134.07 |
| 01:31.7 | 71.5249 | 144.372 | 317.703 | 102.554 | 95.5555 | 133.779 |
| 01:32.3 | 71.2563 | 139.549 | 314.822 | 101.952 | 95.6292 | 133.212 |
| 01:32.9 | 70.4506 | 134.15 | 312.036 | 101.764 | 95.694 | 132.638 |
| 01:33.5 | 70.2322 | 122.247 | 309.242 | 101.575 | 95.5555 | 132.042 |
| 01:34.1 | 70.2537 | 112.948 | 306.383 | 101.773 | 95.6311 | 131.365 |
| 01:34.8 | 69.695 | 110.445 | 303.695 | 100.973 | 95.5753 | 130.813 |
| 01:35.4 | 68.762 | 110.611 | 300.946 | 99.1925 | 95.6508 | 130.28 |
| 01:36.0 | 68.384 | 110.706 | 298.219 | 100.127 | 95.6149 | 129.694 |
| 01:36.6 | 68.7297 | 110.584 | 295.584 | 100.758 | 95.6454 | 129.148 |
| 01:37.2 | 68.1888 | 110.595 | 292.9 | 101.153 | 95.6239 | 128.679 |
| 01:37.9 | 67.5654 | 110.517 | 290.169 | 101.53 | 95.6634 | 128.174 |
| 01:38.5 | 67.2555 | 110.41 | 287.628 | 101.481 | 95.6221 | 127.63 |
| 01:39.1 | 66.6894 | 110.296 | 284.98 | 101.506 | 95.6059 | 127.142 |
| 01:39.7 | 66.6481 | 110.177 | 282.391 | 101.523 | 95.6221 | 126.838 |
| 01:40.3 | 66.5156 | 109.986 | 279.854 | 101.595 | 95.6149 | 126.37 |
| 01:40.9 | 66.5514 | 109.82 | 277.342 | 102.395 | 95.5447 | 125.811 |
| 01:41.6 | 66.2127 | 109.631 | 274.827 | 102.276 | 95.5268 | 125.429 |
| 01:42.2 | 66.2414 | 109.432 | 272.407 | 102.303 | 95.5753 | 125.014 |
| 01:42.8 | 65.2109 | 109.329 | 269.891 | 102.357 | 95.5645 | 124.528 |
| 01:43.4 | 65.0747 | 109.181 | 267.501 | 102.377 | 95.5124 | 123.977 |
| 01:44.0 | 64.6337 | 109.043 | 265.154 | 100.591 | 95.5375 | 123.504 |
| 01:44.7 | 64.666 | 108.855 | 262.779 | 100.517 | 95.5106 | 122.931 |
| 01:45.3 | 64.5566 | 108.69 | 260.531 | 100.311 | 95.4566 | 122.391 |
| 01:45.9 | 63.644 | 108.536 | 258.152 | 100.048 | 95.4422 | 121.882 |
| 01:46.5 | 63.2943 | 108.402 | 255.878 | 100.117 | 95.4045 | 121.279 |
| 01:47.1 | 63.3624 | 108.252 | 253.693 | 99.841 | 95.3883 | 120.832 |
| 01:47.8 | 63.6422 | 107.87 | 251.479 | 99.6986 | 95.3901 | 120.318 |
| 01:48.4 | 63.3965 | 107.785 | 249.286 | 99.6446 | 95.3182 | 119.788 |
| 01:49.0 | 63.3481 | 107.586 | 247.13 | 99.4681 | 95.2481 | 119.298 |
| 01:49.6 | 62.5912 | 107.474 | 245.025 | 99.3222 | 95.2085 | 118.774 |
| 01:50.2 | 62.175 | 107.295 | 242.939 | 99.2897 | 95.2445 | 118.335 |
| 01:50.9 | 61.791 | 107.111 | 240.839 | 99.1276 | 95.1114 | 117.88 |
| 01:51.5 | 61.8969 | 106.968 | 238.804 | 98.9007 | 95.106 | 117.246 |
| 01:52.1 | 61.4447 | 106.838 | 236.79 | 98.7297 | 95.0844 | 116.735 |
| 01:52.7 | 60.3749 | 106.671 | 234.657 | 98.3372 | 95.0179 | 116.191 |
| 01:53.3 | 59.9403 | 106.583 | 232.72 | 98.1319 | 94.9874 | 115.75 |
| 01:54.0 | 59.5686 | 106.393 | 230.719 | 97.9411 | 94.8939 | 115.17 |
| 01:54.6 | 59.6979 | 106.299 | 228.839 | 97.8961 | 94.8849 | 114.678 |
| 01:55.2 | 59.398 | 106.136 | 226.898 | 98.1157 | 94.7321 | 114.144 |
| 01:55.8 | 59.3333 | 106.021 | 224.919 | 97.9393 | 94.6908 | 113.636 |
| 01:56.4 | 58.8519 | 105.88 | 222.977 | 97.9879 | 94.6692 | 113.15 |
| 01:57.1 | 58.3902 | 105.667 | 221.076 | 97.9051 | 94.4643 | 112.487 |

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|---|---|---|---|---|---|---|
| 01:57.7 | 58.0541 | 105.65 | 219.19 | 97.8043 | 94.4984 | 111.891 |
| 01:58.3 | 58.3075 | 105.34 | 217.233 | 97.9357 | 94.4301 | 111.463 |
| 01:58.9 | 57.9499 | 104.939 | 215.359 | 97.8205 | 94.4175 | 110.947 |
| 01:59.5 | 57.8816 | 104.608 | 213.629 | 97.8745 | 94.2378 | 110.617 |
| 02:00.1 | 57.2201 | 102.65 | 211.721 | 97.8277 | 91.5793 | 110.111 |
| 02:00.8 | 57.2308 | 102.821 | 209.95 | 97.6765 | 92.54 | 109.564 |
| 02:01.4 | 56.7274 | 102.769 | 208.202 | 97.5775 | 92.3155 | 109.086 |
| 02:02.0 | 56.2975 | 102.653 | 206.393 | 97.5361 | 92.179 | 108.685 |
| 02:02.6 | 56.3173 | 102.624 | 204.631 | 97.475 | 89.3555 | 108.147 |
| 02:03.2 | 56.2723 | 102.489 | 202.928 | 97.5667 | 88.9644 | 107.655 |
| 02:03.9 | 56.0187 | 102.298 | 201.218 | 97.43 | 88.7061 | 107.145 |
| 02:04.5 | 56.4126 | 102.192 | 199.488 | 97.313 | 88.0138 | 106.615 |
| 02:05.1 | 55.8442 | 101.905 | 197.745 | 97.2914 | 87.3754 | 106.053 |
| 02:05.7 | 55.4933 | 101.878 | 196.034 | 97.2122 | 86.782 | 105.63 |
| 02:06.3 | 54.9408 | 101.831 | 194.313 | 97.2482 | 86.2191 | 105.249 |
| 02:07.0 | 54.8814 | 101.757 | 192.676 | 97.1385 | 85.7477 | 104.722 |
| 02:07.6 | 54.3935 | 101.678 | 191.041 | 97.1079 | 85.2494 | 104.312 |
| 02:08.2 | 54.5015 | 101.602 | 189.391 | 97.1133 | 84.8086 | 103.875 |
| 02:08.8 | 54.19 | 101.519 | 187.837 | 97.0953 | 84.3749 | 103.442 |
| 02:09.4 | 54.0171 | 101.461 | 186.254 | 97.0647 | 83.7228 | 102.922 |
| 02:10.1 | 53.3056 | 101.38 | 184.708 | 97.0053 | 82.9955 | 102.451 |
| 02:10.7 | 52.8316 | 101.306 | 183.243 | 96.9783 | 82.4617 | 101.916 |
| 02:11.3 | 52.774 | 101.137 | 181.731 | 96.8775 | 82.0892 | 101.485 |
| 02:11.9 | 52.61 | 101.075 | 180.284 | 96.9549 | 81.5949 | 101.029 |
| 02:12.5 | 52.2404 | 100.958 | 178.886 | 96.7804 | 81.1489 | 100.63 |
| 02:13.2 | 51.9285 | 100.443 | 177.503 | 96.8775 | 80.6529 | 100.16 |
| 02:13.8 | 52.024 | 99.8428 | 176.001 | 96.7768 | 80.1605 | 99.5761 |
| 02:14.4 | 51.6525 | 99.8986 | 174.673 | 96.6922 | 79.6825 | 99.1817 |
| 02:15.0 | 51.474 | 99.7347 | 173.25 | 96.3415 | 79.2492 | 98.7405 |
| 02:15.6 | 51.0897 | 99.7149 | 171.803 | 96.122 | 78.5707 | 98.2309 |
| 02:16.2 | 50.5682 | 99.5834 | 170.428 | 96.1166 | 77.8367 | 97.6945 |
| 02:16.9 | 50.005 | 99.5761 | 169.004 | 96.0465 | 77.246 | 97.2212 |
| 02:17.5 | 49.6746 | 99.4735 | 167.7 | 96.0051 | 76.7841 | 96.8146 |
| 02:18.1 | 49.624 | 99.4248 | 166.262 | 95.9763 | 76.0574 | 96.2803 |
| 02:18.7 | 48.9719 | 99.1799 | 164.954 | 95.8468 | 75.2483 | 95.7012 |
| 02:19.3 | 48.7785 | 99.0844 | 163.63 | 95.8379 | 74.7077 | 95.3505 |
| 02:20.0 | 48.5508 | 99.0286 | 162.339 | 95.845 | 74.0991 | 94.928 |
| 02:20.6 | 48.2146 | 98.9277 | 160.917 | 95.7425 | 73.6445 | 94.3852 |
| 02:21.2 | 47.9127 | 98.8341 | 159.584 | 96.1796 | 73.3205 | 93.882 |
| 02:21.8 | 47.938 | 98.7387 | 158.299 | 96.0753 | 72.8783 | 93.1759 |
| 02:22.4 | 47.8259 | 98.609 | 156.945 | 95.935 | 72.4505 | 92.3586 |
| 02:23.1 | 47.5094 | 98.5586 | 155.72 | 95.9799 | 72.0602 | 91.5631 |
| 02:23.7 | 47.5275 | 98.4074 | 154.534 | 95.9278 | 71.7111 | 90.7391 |
| 02:24.3 | 46.983 | 98.3642 | 153.275 | 95.9422 | 71.1185 | 90.0302 |
| 02:24.9 | 46.6753 | 98.2633 | 152.086 | 95.854 | 70.6619 | 89.3358 |
| 02:25.5 | 46.6355 | 98.1571 | 150.859 | 95.7695 | 70.277 | 88.7008 |
| 02:26.2 | 46.393 | 98.0329 | 149.724 | 95.7461 | 69.917 | 88.1411 |
| 02:26.8 | 46.2572 | 97.9591 | 148.552 | 95.6994 | 69.5589 | 87.63 |

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| 02:27.4 | 46.2934 | 97.8907 | 147.389 | 95.6886 | 69.181 | 87.0204 |
| 02:28.0 | 46.0707 | 97.7683 | 146.169 | 95.5088 | 68.8408 | 86.3911 |
| 02:28.6 | 45.5546 | 97.7035 | 145.074 | 95.5663 | 68.3428 | 85.753 |
| 02:29.3 | 45.1506 | 97.6243 | 143.917 | 95.4063 | 67.7123 | 85.0182 |
| 02:29.9 | 44.9639 | 97.5469 | 142.738 | 95.3487 | 67.1749 | 84.2961 |
| 02:30.5 | 44.5724 | 97.4606 | 141.687 | 95.4351 | 66.5102 | 83.5848 |
| 02:31.1 | 44.0756 | 97.4102 | 140.491 | 95.4314 | 65.9547 | 82.9149 |
| 02:31.7 | 44.0629 | 97.2608 | 139.408 | 95.4009 | 65.6644 | 82.4205 |
| 02:32.4 | 44.0647 | 97.2572 | 138.353 | 95.6257 | 65.3364 | 81.8904 |
| 02:33.0 | 43.8652 | 97.1978 | 137.216 | 95.5789 | 64.9582 | 81.4247 |
| 02:33.6 | 43.6566 | 97.1312 | 136.118 | 95.5393 | 64.6211 | 80.8553 |
| 02:34.2 | 43.3917 | 97.0377 | 135.019 | 95.498 | 64.2465 | 80.3199 |
| 02:34.8 | 43.1359 | 96.9441 | 134.014 | 95.4207 | 63.8394 | 79.7236 |
| 02:35.4 | 42.9743 | 96.9081 | 132.981 | 95.3487 | 63.3266 | 79.2134 |
| 02:36.1 | 42.5931 | 96.748 | 131.902 | 95.2103 | 62.8244 | 78.5886 |
| 02:36.7 | 42.4188 | 96.7444 | 130.901 | 95.1006 | 62.6127 | 78.0945 |
| 02:37.3 | 42.4969 | 96.6581 | 129.857 | 94.8885 | 62.1929 | 77.5109 |
| 02:37.9 | 42.1936 | 96.5843 | 128.824 | 94.5775 | 61.8628 | 76.956 |
| 02:38.5 | 42.1772 | 96.5123 | 127.775 | 94.2109 | 61.4716 | 76.5514 |
| 02:39.2 | 41.9629 | 96.462 | 126.844 | 93.6484 | 61.2455 | 76.0896 |
| 02:39.8 | 41.7776 | 96.3684 | 125.836 | 93.1004 | 60.7501 | 75.6278 |
| 02:40.4 | 41.5813 | 96.2551 | 124.746 | 92.5256 | 60.3084 | 75.1159 |
| 02:41.0 | 41.2324 | 96.1526 | 123.891 | 91.8755 | 59.7715 | 74.4034 |
| 02:41.6 | 40.9815 | 96.1166 | 122.856 | 91.2148 | 59.2274 | 73.7895 |
| 02:42.3 | 40.676 | 96.0177 | 121.93 | 90.5291 | 58.8214 | 73.2166 |
| 02:42.9 | 40.3195 | 95.9566 | 120.903 | 89.9441 | 58.4081 | 72.7763 |
| 02:43.5 | 40.1685 | 95.8792 | 120.034 | 89.325 | 58.0541 | 72.3932 |
| 02:44.1 | 39.83 | 95.8163 | 119.2 | 88.7241 | 57.7144 | 71.8776 |
| 02:44.7 | 39.7408 | 95.676 | 118.192 | 88.1465 | 57.3639 | 71.3835 |
| 02:45.4 | 39.6571 | 95.7264 | 117.273 | 87.6014 | 57.1086 | 70.9717 |
| 02:46.0 | 39.6353 | 95.5214 | 116.38 | 86.9594 | 56.8353 | 70.5491 |
| 02:46.6 | 39.4132 | 95.3649 | 115.461 | 86.418 | 56.4864 | 70.0907 |
| 02:47.2 | 38.9961 | 95.2229 | 114.504 | 85.8301 | 56.0942 | 69.6216 |
| 02:47.8 | 38.9451 | 95.0449 | 113.59 | 85.253 | 55.8406 | 69.1255 |
| 02:48.5 | 38.9379 | 94.8292 | 112.754 | 84.6509 | 55.5581 | 68.7458 |
| 02:49.1 | 39.0581 | 94.5164 | 111.858 | 84.0363 | 55.3529 | 68.3393 |
| 02:49.7 | 38.7484 | 94.2396 | 111.044 | 83.4612 | 55.1028 | 67.9345 |
| 02:50.3 | 38.7411 | 94.112 | 110.211 | 82.9901 | 54.849 | 67.5708 |
| 02:50.9 | 38.7448 | 93.3915 | 109.378 | 82.4187 | 54.6906 | 67.1265 |
| 02:51.5 | 38.4059 | 92.6927 | 108.466 | 81.8975 | 54.3323 | 66.7897 |
| 02:52.2 | 38.2364 | 92.2041 | 107.628 | 81.3871 | 53.9523 | 66.3507 |
| 02:52.8 | 38.0195 | 91.6295 | 106.818 | 80.8606 | 53.6497 | 65.8884 |
| 02:53.4 | 37.8536 | 91.0479 | 105.97 | 80.3056 | 53.3236 | 65.5855 |
| 02:54.0 | 37.7077 | 90.7212 | 105.269 | 79.7595 | 53.0461 | 65.184 |
| 02:54.6 | 37.4925 | 90.242 | 104.433 | 79.3047 | 52.7055 | 64.7771 |
| 02:55.3 | 37.1715 | 89.6426 | 103.682 | 78.7819 | 52.5144 | 64.4275 |
| 02:55.9 | 37.2025 | 89.1456 | 102.91 | 78.3559 | 52.3143 | 64.0474 |
| 02:56.5 | 37.1314 | 88.6398 | 102.145 | 77.8134 | 51.9826 | 63.6547 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 02:57.1 | 37.0365 | 88.0766 | 101.445 | 77.2478 | 51.8004 | 63.3588 |
| 02:57.7 | 36.7774 | 87.5709 | 100.693 | 76.8325 | 51.501 | 62.9876 |
| 02:58.4 | 36.8595 | 87.0258 | 100.034 | 76.2883 | 51.3134 | 62.5158 |
| 02:59.0 | 36.6588 | 86.6152 | 99.3024 | 75.8873 | 51.0988 | 62.2647 |
| 02:59.6 | 36.458 | 86.1545 | 98.5514 | 75.345 | 50.7523 | 61.8466 |
| 03:00.2 | 36.3557 | 85.7548 | 97.8781 | 74.9315 | 50.5123 | 61.4662 |
| 03:00.8 | 36.1622 | 85.2172 | 97.1312 | 74.4106 | 50.1386 | 61.0355 |

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