Metastable Phase Diagram and Precipitation Kinetics of Magnetic Nanocrystals in FINEMET Alloys

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Abstract
Research over the years has shown that the formation of the Fe\textsubscript{3}Si phase in FINEMET (Fe-Si-Nb-B-Cu) alloys leads to superior soft magnetic properties. In this work, we use a CALPHAD approach to derive Fe-Si phase diagrams to identify the composition-temperature domain where the Fe\textsubscript{3}Si phase can be stabilized. Thereafter, we have developed a precipitation model capable of simulating the nucleation and growth of Fe\textsubscript{3}Si nanocrystals via Langer-Schwartz theory. For optimum magnetic properties, prior work suggests that it is desirable to precipitate Fe\textsubscript{3}Si nanocrystals with 10-15 nm diameter and with the crystalline volume fraction of about 70\%.

Keywords: Soft magnetic alloys, FINEMET, CALPHAD, Thermocalc, TTT Diagram, Fe\textsubscript{3}Si (\(\alpha^\prime\prime\) -(Fe, Si) D0\textsubscript{3}) phase

1. INTRODUCTION
FINEMET is a soft magnetic material based on the Fe-Si-Nb-Cu-B system, developed by Yoshizawa and his group at Hitachi in 1988\textsuperscript{1,2} Due to their high saturation magnetic flux density\textsuperscript{1-2}, low core losses\textsuperscript{1,3}, low magnetostriction\textsuperscript{1-2}, excellent temperature characteristic\textsuperscript{2}, small aging effects\textsuperscript{2} and excellent high frequency characteristics\textsuperscript{1,3}, FINEMET alloys have been used for applications such as mobile phones\textsuperscript{1,24}, noise reduction devices\textsuperscript{25}, computer hard disks\textsuperscript{26} and transformers\textsuperscript{27,28}. Superior soft magnetic properties—in comparison with existing soft magnets at that time, were achieved by crystallizing Fe\textsubscript{3}Si nanocrystals (\(\alpha^\prime\prime\) - (Fe, Si) phase with D0\textsubscript{3} structure) from an amorphous matrix. Optimal properties were achieved for Fe\textsubscript{3}Si nanocrystals with a mean diameter (radius) between 10-15 nm (5-7.5 nm) and volume fraction of about 70\%\textsuperscript{1-17}. Improvements in soft magnetic properties can be achieved by exploring new alloy compositions and by optimizing the current processing\textsuperscript{13-17}. One of the challenges faced with this approach is the scarcity of experimental databases for multi-component systems. Most of the known compositions and associated manufacturing protocols are address the needs of their time. New experiments and the associated materials characterization can be expensive and time consuming. Moreover, engineers working with FINEMET alloys often have to deal with multiple, possibly conflicting, objectives in order to design alloys for specific applications. Hence, it would be beneficial to explore theoretical screening techniques that are based on the physics governing the nucleation and growth, and that can be rapidly and successfully used for testing and screening alloys with compositions not yet studied experimentally.

The CALPHAD approach is one such technique which successfully incorporates advanced models based on several concepts that can explain underlying physics and concomitant phenomena that occur during...
thermal treatment. In recent years, researchers have used the CALPHAD approach to analyze amorphous phases and soft magnets containing amorphous and nanocrystalline phases using the commercial software Thermocalc. The reasons behind using the CALPHAD approach, limitations within the databases, and ways to use the databases have been described in these works. However, simulations of nucleation and growth of critical phases responsible for soft magnetic properties has not been yet been reported.

This motivated us to perform similar investigations in order to address the problem of simulating nucleation and growth of Fe₃Si nanocrystals (D0₃ structure) during isothermal annealing of FINEMET alloys. In this work, we have developed a metastable phase diagram containing the Fe₃Si phase, and a precipitation model capable of simulating nucleation and growth of Fe₃Si nanocrystals during annealing at several reported temperatures. In the model, we were able to crystallize Fe₃Si nanocrystals with a desired mean radius (5-7.5 nm) and volume fraction (70%) by performing isothermal annealing at a set of annealing temperatures for one hour holding time.

2. METHODS

Figure 1 shows the flowchart describing the main steps of this work.

Figure 1: Schematic flowchart outlining the present work on modeling the precipitation kinetics of Fe₃Si nanocrystals in FINEMET.

We used the Thermocalc software for calculating the equilibrium and metastable phase diagrams, and the TC-PRISMA module in Thermocalc to develop a precipitation model capable of simulating nucleation and growth of the Fe₃Si. We used the thermodynamic database TCFE8 for equilibrium calculations, and the mobility database MOBFE3 for simulating the precipitation kinetics of Fe₃Si nanocrystals. We paid particular attention to ensure that we simulated the nucleation and growth of the same phase (i.e., Fe₃Si) that we observed when deriving the metastable phase diagram for the Fe-Si system. Subsequent simulations of nucleation and growth of Fe₃Si nanocrystals during isothermal annealing between 490 °C and 550 °C were performed through the developed precipitation model for 1-2 h holding time. The precipitation model was further used for studying nucleation and growth of Fe₃Si nanocrystals during annealing between 490 °C and 550 °C for compositions in the vicinity of the given composition, Fe₇2.89+ₓSi₁6.2₁−ₓB₆.90Nb₅Cu₁ (where x = ± 3 atomic %).

2.1. Phase Diagrams

There is no Fe₃Si phase in the TCFE8 database, so this exact phase cannot appear in the phase diagrams. However, based on stoichiometry, we surmise that that M₃Si phase in TCFE8 could be the Fe₃Si phase. This phase, however, does not appear in the equilibrium phase diagram of our alloy system. We performed calculations of Gibbs energy-Composition diagram at 540 °C to identify the metastable phases, and found that the M₃Si phase is indeed among them. This lead us to perform phase diagram calculations so as to preferentially stabilize the M₃Si phase. From our plotted metastable phase diagram and reported works on Fe-Si system, we observed that the M₃Si region in TCFE8 database coincides with the previously reported region where Fe₃Si occurs. Hence, in this work we used M₃Si phase to simulate the nucleation and growth of Fe₃Si nanocrystals.

2.2. Time-Temperature-Transformation Diagram of FINEMET

The FINEMET composition used here is Fe₇2.89Si₁6.2₁B₆.90Nb₅Cu₁ in atomic %, or Fe₇2.35Si₉.2₁B₁.5¹Nb₅.6₆Cu₁.₂₉ in weight %. Figure 2 shows the time-temperature-transformation (TTT) diagram of a very similar alloy, Fe₇₃.₅Si₁₆.₅B₁₆.₁Nb₇Cu₂. From Figure 2, we note that it is possible to crystallize only Fe₃Si for temperatures between 773 K (500 °C) and 833 K (560 °C) for holding times between 1.0 and 1.5 h. Additionally, we note that Fe₃Si nanocrystals can be crystallized by annealing for about 200 s holding time at temperatures between about 833 K (560 °C) and 1000 K (727 °C). But isothermal annealing at this temperature for 1 h holding time leads to precipitation of intermetallic Fe-B phases that need to be avoided as they are detrimental for soft magnetic properties.
phase will be precipitated, in this work we focused on performing isothermal annealing at 490 °C, 500 °C, 510 °C, 520 °C, 530 °C, 540 °C and 550 °C for 2 h holding time.

![Figure 2: TTT diagram for FINEMET of composition Fe$_{73.5}$Si$_{18.5}$B$_{6}$Nb$_{3}$Cu$_{1}$](Adapted from Willard and Daniil with permission from Elsevier)

### 3. RESULTS AND DISCUSSION

In this section, we start by determining the region in the Fe-Si phase diagram where the Fe$_3$Si phase is stable (Sec. 3.1). This is followed by results obtained after performing isothermal annealing at various temperatures through the precipitation model (Sec. 3.2). Finally, we use this model for simulating nucleation and growth of Fe$_3$Si nanocrystals by isothermal annealing at various temperatures for new compositions that are in the vicinity of the given composition of FINEMET alloy (Sec. 3.3).

#### 3.1. Equilibrium and Metastable Phase Diagrams

The phases of the Fe-Si system that are present in the TCFE8 database are listed in Table 1 along with their composition and lattice occupancy.

BCC Fe-Si exists in three forms, namely A2 ($\alpha$-(Fe, Si)), B2 ($\alpha'$-(Fe, Si)) and D03 ($\alpha''$-(Fe, Si)). First, we performed equilibrium calculations for the Fe-Si system and plotted the equilibrium Fe-Si phase diagram (Figure 3). We note that B2-BCC is stable up to 30 mole % Si at 1050 °C as a single phase. From 900 °C to about 1400 °C, FCC-A1 is stable as a single phase for up to 3 mole % Si. There is a narrow region between 900 °C and about 1400 °C in which both B2-BCC and FCC-A1 exist. From the lattice occupancy in Table 1 we note that M3SI resembles Fe$_3$Si phase, but M3SI phase does not show in the equilibrium phase diagram (Figure 3). Similarly, BCC-A2 does not appear in the diagram (Figure 3). This means that both BCC-A2 and M3SI could
Table 1: Composition and lattice occupancy of various phases shown in the Fe-Si phase diagram (in lattice occupancy, VA means Vacancy)

| Phase      | Atomic % | Lattice Occupancy                |
|------------|----------|----------------------------------|
| B2 BCC     | 0.915    | (Fe, Si)$_{0.5}$ (Fe, Si)$_{0.5}$ (VA)$_{0.5}$ |
| BCC_A2     | 0.915    | (Fe, Si)$_{1, (VA)}$            |
| M3SI       | 0.750    | (Fe)$_{0.75}$ (Si)$_{0.25}$     |
| FCC_A1     | 0.915    | (Fe, Si)$_{0.5}$ (VA)$_{0.5}$   |
| HCP_A3     | 0.935    | (Fe, Si)$_{1, (VA)}$            |
| FE2SI      | 0.667    | (Fe)$_{0.67}$ (Si)$_{0.33}$     |
| M5SI3      | 0.625    | (Fe)$_{0.62}$ (Si)$_{0.38}$     |
| MSI        | 0.500    | (Fe)$_{0.5}$ (Si)$_{0.5}$       |
| DIAMOND_FCC_A4 | 0.000  | (Si)$_{1}$                      |

Figure 3: The equilibrium Fe-Si phase diagram showing the B2 BCC phase in a large range of temperatures and Si compositions.

be metastable phases. We therefore performed calculations at 540 °C to plot the Gibbs Energy-Composition (or G-X) diagram in order to identify the metastable phases present at 540 °C (Figure 4).

In Figure 4, we observe that at 540 °C, M3SI phase has a higher Gibbs free energy when compared to the BCC A2 and B2 BCC phases. Thus, M3SI is a metastable phase relative to BCC A2 and B2 BCC, which is why it does not appear on the Fe-Si equilibrium phase diagram (Figure 3). Before we proceed, it is important to identify the temperature-composition region in which M3SI can appear in the Fe-Si phase diagram. In Thermocalc, all computed phase diagrams are equilibrium ones, hence they will not contain metastable phases. In order to find the conditions for which M3SI can exist, we circumvent this by suppressing one or more phases from equilibrium calculation. Based on the G-x plots (Figure 4), we remove the B2 BCC and BCC A2 phases from the phase diagrams, and re-evaluate the remaining competing phases. The result is the metastable phase diagram in Figure 5, which shows that the M3SI phase exists in the region between about 15 to 25 mole % Si; also, the M3SI phase co-exists with the M5SI3 phase from 25 - 37 mole % Si.

On comparing Figure 5 with works studying both the Fe-Si binary system and the FINEMET alloys, we notice that the region of occurrence of the M3SI phase coincides with the region in which the Fe$_3$Si phase has been observed. This confirms that the M3SI phase can be used to simulate nucleation and growth of Fe$_3$Si nanocrystals from the amorphous phase (Sec. 2.3).

3.2. Simulating Nucleation and Growth of M3SI (Fe$_3$Si) in TC-PRISMA

Based on guidelines in Sec. 2.3, we developed a precipitation model capable of simulating nucleation and growth of M3SI (Fe$_3$Si) nanocrystals in the TC-PRISMA module of Thermocalc. The TTT diagrams...
(Figure 4) shows that it is possible to precipitate only Fe₃Si for isothermal annealing at 540 °C (813 K) for 1.5 h holding time, with no inter-metallic Fe-B phase appearing even for prolonged holding times. In order to examine the effects of changing the temperature, we used the developed model to perform isothermal annealing at 490, 500, 510, 520, 530, 540 and 550 °C for precipitating M₃Si (Fe₃Si) nanocrystals for 2 h, at the nominal composition of Fe₇₂.₈₉Si₁₆.₂₁B₆.₉₀Nb₃Cu₅ (atomic %).

**Mean Radius vs Time** Figure 6 shows the variation of mean radius of M₃Si (Fe₃Si) nanocrystals as a function of holding time for various annealing temperatures. At 1 h holding time, we were able to achieve a mean radius above 5 nm but below 6 nm (Table 2), which is in the desired range. Another important observation is that mean radius increases with the annealing temperature Figure 6, which is also apparent in a plot of the size distribution plot (Figure 7).

**Size Distribution** Figure 7 shows the size distribution of M₃Si (Fe₃Si) nanocrystals for various annealing temperatures for 1 h and 2 h holding times. For 1 h holding time, the maximum mean radius is around 8 nm, while for 2 h holding time the mean radius is about 10 nm. In the latter case, the mean size is out of the the desired range. The area under the size distribution plot for any of the curves provides the number density of M₃Si (Fe₃Si) nanocrystals/m³ with nanocrystal sizes within the range shown in Figure 7 for a particular isothermal annealing temperature and holding time. The number density obtained for the precipitated M₃Si (Fe₃Si) nanocrystals is consistent with those reported in literature. Thus, for the current annealing conditions, we were able to obtain optimum mean radius by isothermal annealing at all the annealing temperatures under consideration for 1 h time. We can now proceed to estimating the volume fraction of M₃Si (Fe₃Si) obtained after isothermal annealing through our model.

**Volume Fraction vs. Time** In Sec. 1 we mentioned that the target nanocrystalline volume fraction is about 70 %. Figure 8 shows the variation of volume fraction as a function of time for during isothermal annealing at various annealing temperatures for up to 1 h holding time. We were able to achieve the desired volume fraction of 70 % for all temperatures under consideration after 1 h annealing. The volume fraction obtained after 1 h, 1.5 h, and 2 h has been tabulated in Table 2. The volume fraction of precipitated M₃Si (Fe₃Si) nanocrystals decreases with increase in annealing temperatures for the same holding time.

Additional information regarding the nucleation rate (Appendix 6.1.1), number density (Appendix 6.1.2), and driving force (Appendix 6.1.3) for crystallization of M₃Si (Fe₃Si) nanocrystals has been included in the Appendix. This information can be used to support the volume fraction results shown here. The observed nucleation rate and number density is in accordance with reported experimental work on FINEMET alloys.
Figure 5: Metastable Fe-Si phase diagram showing the M3SI phase, obtained by suppressing the B2_BCC and BCC_A2 phases from the equilibrium phase diagram.

Table 2: Mean radius of Fe₃Si nanocrystals during isothermal annealing at various annealing temperatures for different holding times

| Temp. (°C) | Mean radius (nm) | Volume fraction | Silicon (mole %) |
|-----------|------------------|-----------------|------------------|
|           | 1.0 h   | 1.5 h  | 2.0 h | 1.0 h   | 1.5 h  | 2.0 h | 1.0 h   | 1.5 h  | 2.0 h |
| 490       | 5.0      | 5.75   | 6.3   | 0.7060  | 0.7064 | 0.7066 | 1.809   | 1.787  | 1.771 |
| 500       | 5.1      | 5.85   | 6.4   | 0.7038  | 0.7041 | 0.7045 | 1.947   | 1.927  | 1.904 |
| 510       | 5.2      | 5.95   | 6.5   | 0.7015  | 0.7020 | 0.7022 | 2.085   | 2.059  | 2.046 |
| 520       | 5.3      | 6.05   | 6.65  | 0.6989  | 0.6995 | 0.6998 | 2.244   | 2.210  | 2.190 |
| 530       | 5.4      | 6.15   | 6.75  | 0.6962  | 0.6969 | 0.6973 | 2.404   | 2.365  | 2.340 |
| 540       | 5.5      | 6.25   | 6.85  | 0.6936  | 0.6944 | 0.6947 | 2.557   | 2.513  | 2.496 |
| 550       | 5.6      | 6.35   | 7.0   | 0.6909  | 0.6913 | 0.6919 | 2.716   | 2.689  | 2.660 |

Matrix Composition vs. Time Figure 9 shows the variation of matrix composition for annealing at 490 and 550 °C. We can observe that there is a significant difference in matrix composition of various elements for the two temperatures over the course of isothermal annealing for 2 h. The Si content is significantly lower for annealing at 490 °C as compared to annealing at 550 °C. This can be understood from the fact that the volume fraction of the M3SI (Fe₃Si) phase is higher at 490 °C when compared to volume fraction at 550 °C (Figure 8 and Table 2 in Sec. 3.2). Thus, more silicon went into the formation of M3SI (Fe₃Si) nanocrystals and hence, less Si remained in the matrix at 490 °C. The matrix composition of Si obtained after isothermal annealing for 1, 1.5, and 2 h holding time
for various annealing temperatures is listed in Table 2. These values for niobium, boron and copper have been tabulated and are included in Appendix 6.1.4, Table 3.

3.3. Using the precipitation model for Fe₃Si nanocrystals from matrices of different compositions

In Sec. 3.2, we have shown the scope of application of our proposed CALPHAD model as an effective predictive tool and used it for simulating nucleation and growth of M₃SI (Fe₃Si) nanocrystals from an amorphous precursor. We can also apply this model to FINEMET alloys of different compositions. To this end, we altered the variable bounds of Fe and Si by ±3 atomic %, and performed isothermal annealing at the temperatures mentioned in Sec. 3.2 for 2 h holding time. The new compositions can be written as Feₓ₇₂.₈₉₋ₓ,Si₁₆.₂₁₋ₓ,Bₓ⁰₆₋ₓ,NbₓCu₁ (where x = ±3 atomic % or x = [3, 2, 1, 0, -1, -2, -3]). The following figures show the variation of mean radius (Figure 10) and volume fraction (Figure 11) during isothermal annealing at 490 °C for 2 h holding time for these compositions.

Mean Radius for varying composition Figure 10 shows the mean radius of M₃SI (Fe₃Si) nanocrystals during isothermal annealing at 490 °C for a 2 h holding time for various x values. As x increases (Fe increases and Si decreases), mean radius decreases for isothermal annealing at 490 °C displaying a saturation behavior as the mean radius for x = 2 and x = 3 are very close to one another. For x < 0, the mean radius obtained after annealing at 490 °C is less than 5 nm, i.e. outside the desired range. Therefore, for x < 0, one has to increase the annealing time above 1 h for to obtain a mean radius above 5 nm.

Volume fraction for varying composition Figure 11 shows the variation of volume fraction of M₃SI (Fe₃Si) nanocrystals during isothermal annealing at 490 °C for a 2 h holding time for various composition of FINEMET obtained by varying x. As x increases (Fe increases and Si decreases), the volume fraction decreases for isothermal annealing at 490 °C. Additionally, for x < 0, the volume fraction obtained after isothermal annealing at 490 °C is less than the desired 70%, even for prolonged holding time. At x = 3, the volume fraction is as low as 55%. Still this volume fraction is within the range of volume fraction reported in other studies on FINEMET alloys.

From Figures 10 and 11 we note that both mean radius and volume fraction decrease with increasing x. This trend was also observed for isothermal annealing at 500°C, 510°C, 520°C, 530°C, 540°C and 550°C. Thus, it is important to focus on Fe-Si content to achieve the desired mean radius and volume fraction for optimum properties.

4. CONCLUSIONS

In this work, we laid the guidelines for developing a precipitation model within Thermocalc for simulating nucleation and growth of Fe₃Si nanocrystals from an
amorphous precursor of soft magnetic FINEMET alloy. Fe$_3$Si phase was identified as the M3Si in the TCFE8 database by plotting metastable phases on the Fe-Si phase diagram and comparing the metastable M3Si phase in TCFE8 database with various studies on Fe-Si system that had reported the Fe$_3$Si (D03) phase. Thereafter, we used this M3Si phase and developed a precipitation model for studying the nucleation and growth of magnetic M3Si (Fe$_3$Si) nanocrystals during isothermal annealing for a set of annealing temperatures (490-550 °C) for up to 2 h holding time. During isothermal annealing, the mean radius increases with increase in annealing temperature while volume fraction decreases with increase in temperature.

Results obtained from precipitation model during isothermal annealing at various annealing temperatures (490-550 °C) correlate well with the observations reported in the literature regarding mean radius, size range and volume fraction. Thus, we proceeded with using this precipitation model for new compositions that are in the vicinity of the nominal FINEMET composition. Isothermal annealing was performed on these new compositions for the same set of annealing temperatures (490 °C - 550 °C), for 2 h holding time. We found that with decrease in Silicon content, both mean radius and volume fraction increases for all the annealing temperatures under consideration.

In conclusion, we developed a robust precipitation model under the framework of CALPHAD approach that is capable of simulating nucleation and growth of M3Si or Fe$_3$Si nanocrystals from an amorphous precursor for a class of FINEMET alloy by isothermal annealing at a set of annealing temperatures (490 °C - 550 °C) for 2 hour holding time. Subject to careful parameterization, this model can be used to study the precipitation of crystalline phases for other alloys with large number of atomic species, or even for the same FINEMET alloys but for different crystals (e.g., copper nanoparticles that are believed to act as nucleation sites for the D03 phase).

5. ACKNOWLEDGMENT

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6. APPENDIX

6.1. Results

Results reported in this section support the findings reported in Sec. 3.2.

6.1.1. Nucleation Rate vs. Time

Figure 12 shows the plot for variation of nucleation rate of M3Si (Fe$_3$Si) nanocrystals during isothermal annealing at various annealing temperatures (490-550 °C) for 2 hour holding time. It can be observed that nucleation ends after about 1 minute. Additionally, nucleation rates decreases with increase in temperature, where the nucleation rate decreases by 6 orders of magnitude in a few seconds. This plot can be helpful in understanding the volume fraction plot (Figure 8) and Table 2 reported in Sec. 3.2, where we observed that volume fraction decreases with increase in temperature. After one minute, radius will increase by growth mechanism of preexisting nucleus and hence, less number of nucleus at higher temperature can be responsible for comparatively less volume fraction obtained when annealing is performed at elevated temperatures. Observed nucleation rate is in accordance with reported literature on FINEMET alloys.

6.1.2. Number Density vs. Time

Figure 13 shows the plot of variation of number density of M3Si (Fe$_3$Si) nanocrystals during isothermal annealing at various annealing temperatures (490-550 °C) for 2 hour holding time. Here too, we can observe a
slight decrease in number density with increase in temperature. Thus lower number of precipitates with increase in annealing temperatures can be another reason for lower volume fraction at elevated temperatures (Figure 8 and Table 2 reported in Sec. 3.2). Reported number density is in accordance with reported work on FINEMET alloys\cite{15,17}.

Figure 13: Number density (of M3SI (Fe3Si)) vs Time during isothermal annealing at various annealing temperatures.

6.1.3. Driving Force vs Time

Figure 14 shows variation of driving force of formation of M3SI (Fe3Si) nanocrystal during isothermal annealing at various annealing temperatures (490-550 °C) for 2 hour holding time. Here, too we can observe that driving force decreases with increase in temperature. This can explain the decrease in nucleation rate, number density and thus decrease in volume fraction with increase in isothermal annealing temperature (Figure 8 and Table 2 reported in Sec. 3.2).

Figure 14: Driving Force (of formation of M3SI (Fe3Si) nanocrystal) vs. Time during isothermal annealing at various annealing temperatures.

6.1.4. Matrix Composition

In this section, matrix composition of Niobium, Boron and Copper obtained after isothermal annealing at a set of annealing temperatures (490 °C - 550 °C) for 3600, 5400 and 7200 seconds holding time has been tabulated in Table 3. Figure 9 in Sec. 3.2 shows the variation of matrix composition (mole %) during isothermal annealing at 490 °C and 550 °C for Silicon, Niobium, Boron and Copper.

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Table 3: Matrix Composition of Niobium during isothermal annealing at various annealing temperatures for 3600, 5400 and 7200 seconds holding time

| Temp. (°C) | Niobium (mole %) | Boron (mole %) | Copper (mole %) |
|------------|------------------|----------------|----------------|
|            | 3600 s | 5400 s | 7200 s | 3600 s | 5400 s | 7200 s | 3600 s | 5400 s | 7200 s |
| 490        | 7.915  | 7.922  | 7.928  | 18.210 | 18.228 | 18.241 | 2.647  | 2.649  | 2.651  |
| 500        | 7.868  | 7.875  | 7.883  | 18.103 | 18.118 | 18.136 | 2.631  | 2.633  | 2.636  |
| 510        | 7.868  | 7.875  | 7.883  | 17.994 | 18.014 | 18.024 | 2.615  | 2.618  | 2.620  |
| 520        | 7.767  | 7.778  | 7.785  | 17.869 | 17.896 | 17.911 | 2.597  | 2.601  | 2.60   |
| 530        | 7.712  | 7.725  | 7.734  | 17.744 | 17.774 | 17.794 | 2.579  | 2.583  | 2.586  |
| 540        | 7.660  | 7.675  | 7.681  | 17.6231| 17.6579| 17.672 | 2.561  | 2.566  | 2.568  |
| 550        | 7.605  | 7.615  | 7.625  | 17.498 | 17.520 | 17.543 | 2.543  | 2.546  | 2.550  |

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