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# Thermal Conductivity of Steam from 250 to 510°C at Pressures up to 95 MPa Including the Critical Region

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New measurements of the thermal conductivity of steam have been performed in the temperature range 250–510°C and in the pressure range from 1 up to 95 MPa. Most of the measurements were taken at temperatures greater than the critical temperature, where the enhancement of the thermal conductivity is observed. The experimental values are compared to the IAPS formulation for the thermal conductivity of water.

**KEY WORDS:** critical range; high pressure; thermal conductivity; steam.

## 1. INTRODUCTION

In this paper, we present a new set of experimental values of the thermal conductivity of steam in the temperature range 250–510°C up to 95 MPa. The data have been obtained by using a coaxial cylinder cell which allows us to carry out accurate measurements over large temperature and pressure ranges, including the critical region, provided that care is taken to ensure that the convection and the radiation remain small compared to the heat transfer by conduction.

This investigation was justified by the fact that, up to now, the data in the critical range are scarce, the only detailed investigations having been made by Sirota et al. [1, 2] and, to a lesser extent, by Le Neindre et al. [3]. Moreover, it must be noted that the correlation proposed by Sengers et al. [4] and adopted by the International Association for the Properties

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of Steam (IAPS) shows systematic deviations when compared to these experimental data.

## 2. EXPERIMENTAL METHOD

The coaxial cylinder cell was described previously in the literature [5–7]. It has been used to measure the thermal conductivity of $D_2O$ in the same temperature and pressure ranges [8]. The gap between the cylinders was 0.2 mm.

The thermal conductivity $\lambda$ of the fluid is calculated by Fourier's law with a number of corrections to take into account the heat losses by solid interfaces (centering pins, electrical wires, thermocouples) and the heat transferred by convection ($Q_c$) and radiation ($Q_r$).

To determine the heat conduction by solids, which is a function of the temperature and the thermal conductivity of the sample, a calibration has to be made with noble gases at pressures sufficiently high to avoid accommodation effects (1 MPa for Xe, Kr, and Ar and 10 MPa for Ne and He).

The convection which takes place in the cell is assumed to be laminar. In that case, the correction for convection is approximated by the relation [9],

$$Q_c = \mathrm{Ra}\,\frac{2\pi r}{720}\,\lambda\,\Delta T \tag{1}$$

where Ra is the Rayleigh number, $r$ is the radius of the inner cylinder ($r = 0.01$ m), and $\Delta T$ is the temperature difference between the cylinders. Our measurements where not made at temperatures $T$ too close to the critical temperature $T_c$ ($T - T_c > 5$ K) so that the maximum correction due to convection evaluated from Eq. (1) is not larger than a few percent of the total heat transfer.

The radiation heat transfer can be a source of large errors in measuring the thermal conductivity of fluids. In order to minimize its influence, the cell is made of pure silver and the wetted walls are carefully polished. Whatever form is used to evaluate the radiation correction (transparent fluid, absorbing medium [10, 11], its contribution is less than 1% of the total heat transfer in the entire range of this investigation.

## 3. RESULTS

About 200 experimental points were measured (Table AI in the Appendix, Fig. 1). Most of the measurements were carried out above the

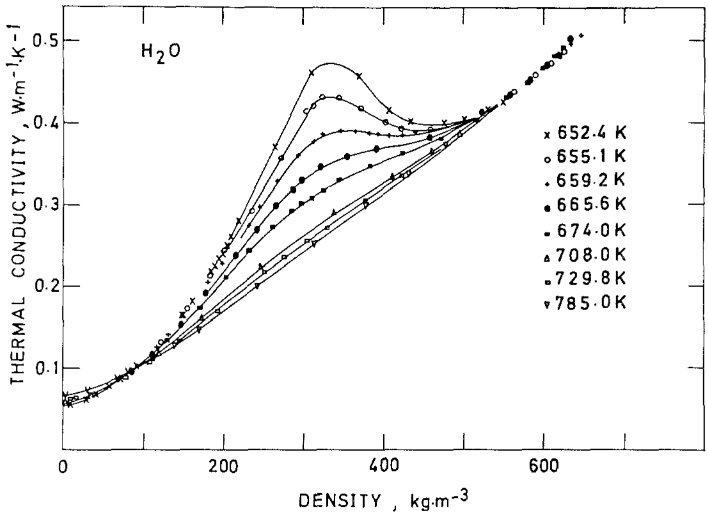


**Fig. 1.** Thermal conductivity of steam as a function of temperature and density.

critical temperature $T_c$ ($T_c = 647.13$ K) along quasi-isotherms up to 784 K. The temperature change along a quasi-isotherm is related to the change in the temperature gradient in the sample and to the heat transfer modification between the cell and the high-pressure vessel.

The temperature was measured with a 0.02 K accuracy. The pressure was measured with an accuracy of 10 kPa up to 30 MPa and of 50 kPa above 30 MPa.

The densities $\rho$ reported in column 3 of Table AI have been calculated from the equation of state reported by Haar et al. [12]; a scaled equation of state would not change significantly the calculated densities in the temperature range of this study.

## 4. COMPARISON WITH PREVIOUS MEASUREMENTS

The present data and the results obtained by Le Neindre et al. [3], who used the same type of apparatus, are in agreement with their respective 2% claimed accuracy.

The comparison with the data of Sirota et al. [2] shows deviations which amount to 10% in the density range 200 to 400 $\text{kg} \cdot \text{m}^{-3}$ up to 673 K. The two data sets cannot be brought into accord by taking into account only the claimed accuracy of the measurements.

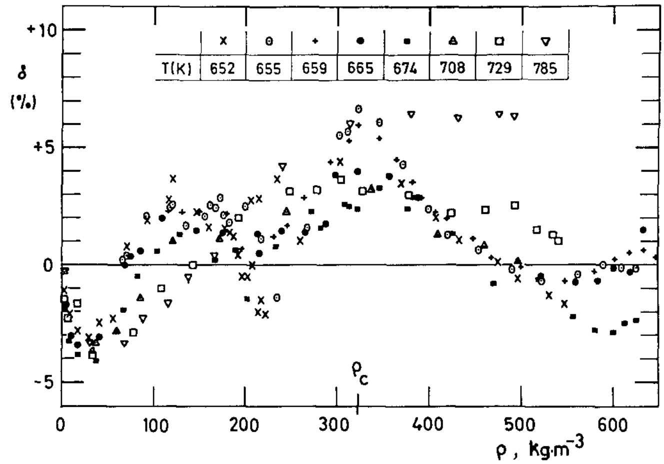


**Fig. 2.** Deviations of the experimental thermal conductivity data for steam from equation given by Sengers et al. [4].

## 5. COMPARISON WITH IAPS REPRESENTATIVE EQUATION

The deviation $\delta$ between our experimental values of the thermal conductivity of steam and the values calculated from the equation proposed by Sengers et al. [4] and adopted by the IAPS are given in the last column of Table AI and shown in Fig. 2. Although systematic deviations can be observed, most of the experimental values are within the assigned tolerances of the equation.

We emphasize that the agreement is better ($\delta < 3\,\%$) with the critically evaluated data reduced to a uniform grid reported in Ref. 4 for 784 K and for densities lower than $80\ \mathrm{kg \cdot m^{-3}}$.

## 6. CONCLUSION

In this paper we have presented new accurate results of the thermal conductivity of steam, mainly at temperatures greater than the critical temperature over a wide density range. The present data should help to improve the representative correlation.

## APPENDIX

**Table AI.** Thermal Conductivity of $H_2O$

| $T$ (K) | $P$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\lambda$ ($mW \cdot m^{-1} \cdot K^{-1}$) | $\delta$ (%) |
|---|---|---|---|---|
| 623.25 | 16.12 | 104.6 | 134.2 | +10.4 |
| 623.27 | 14.91 | 85.9 | 108.3 | +9.0 |
| 623.63 | 12.40 | 61.1 | 80.9 | +3.3 |
| 623.76 | 9.91 | 44.0 | 67.6 | 0.0 |
| 623.68 | 4.92 | 18.9 | 53.9 | −3.5 |
| 623.82 | 2.41 | 8.76 | 50.5 | −2.4 |
| 623.94 | 0.94 | 3.32 | 49.1 | −1.9 |
| 630.17 | 50.60 | 680.9 | 527.2 | +3.0 |
| 630.89 | 45.00 | 667.1 | 513.9 | +2.3 |
| 631.80 | 40.00 | 652.2 | 500.1 | +1.7 |
| 632.46 | 35.00 | 635.4 | 485.9 | +1.2 |
| 633.10 | 30.00 | 614.8 | 470.9 | +0.9 |
| 634.31 | 25.17 | 585.7 | 449.2 | 0.0 |
| 635.29 | 19.94 | 530.8 | 425.0 | +0.2 |
| 628.03 | 17.37 | 121.9 | 158.9 | +10.3 |
| 627.06 | 16.90 | 113.0 | 143.8 | +9.7 |
| 626.72 | 15.95 | 96.6 | 119.2 | +8.3 |
| 626.75 | 14.95 | 83.5 | 102.4 | +6.2 |
| 650.78 | 30.23 | 547.8 | 424.2 | −1.7 |
| 650.97 | 28.35 | 529.7 | 415.9 | −1.3 |
| 651.34 | 26.13 | 497.8 | 404.2 | −0.6 |
| 651.59 | 25.10 | 473.8 | 399.5 | +0.1 |
| 651.75 | 24.07 | 432.8 | 403.0 | +1.1 |
| 652.00 | 23.81 | 406.8 | 416.1 | +2.0 |
| 652.18 | 23.60 | 370.0 | 457.6 | +3.5 |
| 652.43 | 23.43 | 303.2 | 462.2 | +4.4 |
| 652.61 | 23.30 | 260.0 | 370.5 | +1.0 |
| 652.94 | 23.20 | 233.7 | 320.2 | +3.7 |
| 652.95 | 23.02 | 215.6 | 280.7 | +2.9 |
| 653.09 | 22.92 | 206.0 | 261.1 | +2.8 |
| 653.05 | 23.11 | 221.9 | 278.4 | −2.1 |
| 652.68 | 23.0 | 218.4 | 275.3 | −1.5 |
| 652.37 | 22.90 | 214.9 | 268.6 | −2.0 |
| 652.32 | 22.80 | 207.6 | 259.9 | 0.0 |
| 652.16 | 22.70 | 202.6 | 249.7 | −0.5 |
| 652.03 | 22.60 | 197.6 | 240.6 | −0.5 |
| 651.98 | 22.50 | 192.2 | 233.2 | +0.4 |
| 651.93 | 22.39 | 186.8 | 225.4 | +1.2 |
| 651.89 | 22.29 | 182.2 | 217.8 | +1.4 |
| 651.82 | 22.19 | 178.3 | 211.7 | +1.6 |

Table AI. *(Continued)*

| $T$ (K) | $P$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\lambda$ ($mW \cdot m^{-1} \cdot K^{-1}$) | $\delta$ (%) |
|---|---|---|---|---|
| 651.74 | 21.65 | 159.3 | 181.5 | +1.6 |
| 651.83 | 21.17 | 146.1 | 163.6 | +2.3 |
| 651.66 | 19.80 | 120.4 | 133.2 | +3.7 |
| 653.34 | 19.72 | 116.7 | 127.5 | +2.8 |
| 651.72 | 17.48 | 91.8 | 102.5 | +1.9 |
| 651.73 | 15.08 | 71.2 | 85.6 | +0.8 |
| 651.08 | 12.57 | 54.6 | 72.9 | −2.3 |
| 651.18 | 10.06 | 40.7 | 65.8 | −2.5 |
| 651.22 | 7.50 | 28.6 | 60.2 | −3.1 |
| 651.37 | 4.94 | 17.8 | 56.4 | −2.8 |
| 651.56 | 2.33 | 8.0 | 53.5 | −2.1 |
| 651.94 | 0.93 | 3.1 | 52.5 | −1.1 |
| 654.79 | 50.30 | 626.7 | 486.7 | −0.1 |
| 654.87 | 45.00 | 609.4 | 473.1 | −0.1 |
| 655.01 | 40.10 | 589.6 | 459.2 | 0.0 |
| 655.10 | 35.05 | 563.0 | 439.2 | −0.4 |
| 655.25 | 30.00 | 522.5 | 413.7 | −0.7 |
| 655.30 | 27.64 | 490.9 | 400.9 | −0.2 |
| 655.47 | 26.11 | 455.1 | 392.6 | +0.6 |
| 655.22 | 25.16 | 420.7 | 394.0 | +1.3 |
| 655.16 | 24.84 | 400.8 | 401.3 | +2.4 |
| 655.10 | 24.53 | 372.2 | 417.4 | +4.3 |
| 655.06 | 24.33 | 344.7 | 430.8 | +6.1 |
| 655.04 | 24.20 | 321.8 | 430.8 | +6.7 |
| 655.08 | 24.16 | 311.9 | 421.4 | +5.7 |
| 654.99 | 24.09 | 302.6 | 415.9 | +5.6 |
| 655.07 | 23.91 | 267.0 | 356.9 | +1.6 |
| 655.25 | 23.68 | 233.8 | 291.0 | −1.4 |
| 655.31 | 23.48 | 216.1 | 266.9 | +1.1 |
| 655.44 | 23.26 | 200.6 | 243.4 | +2.5 |
| 654.84 | 22.76 | 181.8 | 212.1 | +1.8 |
| 654.12 | 21.78 | 153.7 | 171.8 | +2.1 |
| 653.62 | 19.96 | 119.8 | 130.5 | +2.6 |
| 653.07 | 17.53 | 91.3 | 102.1 | +2.1 |
| 652.64 | 15.00 | 70.2 | 84.6 | +0.4 |
| 654.57 | 14.54 | 66.3 | 81.9 | +0.2 |
| 655.78 | 22.77 | 176.4 | 202.9 | +2.1 |
| 655.99 | 22.70 | 172.8 | 198.7 | +2.9 |
| 656.19 | 22.58 | 168.0 | 190.4 | +2.4 |
| 656.32 | 22.40 | 162.1 | 182.2 | +2.6 |
| 656.58 | 22.19 | 155.6 | 172.2 | +2.1 |
| 656.07 | 21.18 | 135.5 | 146.3 | +1.7 |
| 656.08 | 20.16 | 119.1 | 128.7 | +2.5 |
| 657.55 | 59.75 | 645.7 | 505.1 | +0.3 |

Table AI. *(Continued)*

| $T$ (K) | $P$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\lambda$ ($mW \cdot m^{-1} \cdot K^{-1}$) | $\delta$ (%) |
|---|---|---|---|---|
| 657.57 | 55.10 | 633.8 | 496.3 | +0.6 |
| 657.69 | 50.00 | 618.7 | 483.8 | +0.5 |
| 657.94 | 45.20 | 601.7 | 469.1 | +0.2 |
| 658.12 | 40.00 | 579.1 | 450.6 | −0.3 |
| 658.51 | 34.82 | 547.7 | 427.8 | −0.7 |
| 658.80 | 29.94 | 499.8 | 403.4 | −0.1 |
| 658.91 | 28.13 | 468.7 | 391.5 | +0.3 |
| 658.96 | 27.28 | 446.9 | 387.6 | +1.1 |
| 659.07 | 26.59 | 420.6 | 385.6 | +2.0 |
| 659.15 | 26.32 | 406.0 | 384.8 | +2.3 |
| 659.17 | 26.09 | 391.9 | 386.0 | +2.9 |
| 659.18 | 25.94 | 381.1 | 387.9 | +3.5 |
| 659.18 | 25.74 | 364.7 | 390.2 | +4.5 |
| 659.17 | 25.54 | 345.3 | 390.9 | +5.4 |
| 659.17 | 25.34 | 322.7 | 386.2 | +6.0 |
| 659.20 | 25.26 | 312.1 | 378.2 | +5.3 |
| 659.30 | 25.12 | 292.2 | 360.1 | +4.4 |
| 659.35 | 24.90 | 266.5 | 328.7 | +2.9 |
| 659.44 | 24.68 | 244.2 | 295.8 | +1.7 |
| 659.49 | 24.50 | 229.7 | 273.5 | +1.2 |
| 658.69 | 23.78 | 197.7 | 227.0 | +0.7 |
| 658.35 | 23.26 | 179.3 | 203.6 | +2.2 |
| 658.04 | 22.10 | 149.0 | 162.7 | +2.3 |
| 756.57 | 21.07 | 130.7 | 140.6 | +2.3 |
| 657.12 | 19.96 | 115.0 | 123.9 | +2.3 |
| 663.37 | 60.00 | 634.0 | 501.6 | +1.5 |
| 663.55 | 55.10 | 620.2 | 481.4 | −0.3 |
| 663.64 | 50.10 | 604.1 | 470.2 | −0.1 |
| 664.01 | 45.00 | 583.5 | 452.0 | −0.7 |
| 664.46 | 40.20 | 558.5 | 434.3 | −0.8 |
| 664.61 | 35.00 | 521.5 | 412.2 | −0.5 |
| 665.00 | 30.12 | 454.7 | 382.0 | +0.7 |
| 665.14 | 28.09 | 389.9 | 368.0 | +2.9 |
| 665.37 | 27.52 | 354.7 | 359.9 | +3.8 |
| 665.61 | 27.11 | 321.8 | 345.8 | +4.0 |
| 665.79 | 26.84 | 298.2 | 330.6 | +3.9 |
| 665.34 | 26.58 | 287.3 | 317.7 | +1.8 |
| 665.29 | 26.27 | 265.7 | 297.6 | +1.4 |
| 665.42 | 25.88 | 239.3 | 269.0 | +1.5 |
| 664.87 | 25.28 | 214.6 | 237.2 | +0.5 |
| 664.12 | 25.09 | 212.4 | 237.7 | +1.3 |
| 664.31 | 24.08 | 175.8 | 189.9 | +1.4 |
| 663.72 | 22.60 | 144.7 | 152.6 | +1.5 |

Table AI. *(Continued)*

| $T$ (K) | $P$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\lambda$ ($mW \cdot m^{-1} \cdot K^{-1}$) | $\delta$ (%) |
|---|---|---|---|---|
| 663.67 | 20.00 | 108.3 | 115.6 | +2.0 |
| 662.47 | 17.49 | 85.3 | 95.1 | +0.6 |
| 660.25 | 15.97 | 74.4 | 87.3 | +0.4 |
| 661.51 | 15.02 | 67.3 | 82.4 | 0.0 |
| 661.51 | 9.98 | 39.0 | 65.4 | −3.1 |
| 661.18 | 4.97 | 17.6 | 56.9 | −3.4 |
| 660.91 | 2.50 | 8.5 | 54.2 | −3.0 |
| 660.90 | 0.99 | 3.3 | 53.3 | −1.7 |
| 672.18 | 63.50 | 624.3 | 490.1 | −2.4 |
| 672.69 | 60.00 | 613.5 | 479.8 | −2.5 |
| 672.66 | 55.20 | 598.6 | 464.7 | −2.9 |
| 673.02 | 50.00 | 578.4 | 448.5 | −2.8 |
| 673.36 | 45.10 | 554.6 | 432.0 | −2.2 |
| 673.68 | 40.00 | 521.4 | 408.5 | −0.6 |
| 673.97 | 35.00 | 469.8 | 380.2 | −0.8 |
| 674.17 | 32.50 | 424.5 | 363.3 | +1.3 |
| 674.24 | 31.00 | 382.3 | 348.7 | +2.9 |
| 671.74 | 30.00 | 376.5 | 348.7 | +2.4 |
| 674.28 | 30.02 | 344.1 | 331.8 | +3.3 |
| 674.01 | 29.48 | 323.1 | 318.3 | +2.4 |
| 673.96 | 29.24 | 312.2 | 312.2 | +2.5 |
| 673.95 | 29.14 | 307.5 | 309.7 | +2.6 |
| 673.96 | 28.94 | 297.5 | 302.2 | +2.3 |
| 673.52 | 28.56 | 284.2 | 291.7 | +1.6 |
| 673.46 | 28.04 | 259.9 | 270.6 | +1.2 |
| 673.19 | 27.36 | 233.2 | 244.3 | +0.8 |
| 672.75 | 26.34 | 200.9 | 209.3 | −1.5 |
| 673.41 | 26.09 | 190.8 | 197.1 | +0.6 |
| 672.73 | 25.00 | 167.9 | 171.3 | +0.2 |
| 672.69 | 22.54 | 128.3 | 131.6 | +1.3 |
| 671.94 | 20.03 | 101.7 | 107.3 | +0.6 |
| 671.34 | 17.53 | 81.3 | 91.2 | −0.5 |
| 670.86 | 15.02 | 64.6 | 79.6 | −1.9 |
| 669.88 | 10.02 | 38.3 | 65.1 | −4.1 |
| 669.51 | 4.99 | 17.4 | 57.5 | −3.8 |
| 669.11 | 2.51 | 8.4 | 55.0 | −3.1 |
| 668.87 | 0.99 | 3.3 | 54.1 | −1.9 |
| 708.68 | 55.00 | 494.7 | 386.4 | +0.1 |
| 708.36 | 49.90 | 459.4 | 363.9 | +0.8 |
| 708.29 | 45.00 | 410.7 | 332.4 | +1.3 |
| 708.16 | 40.00 | 337.4 | 290.2 | +3.2 |
| 707.72 | 35.00 | 245.2 | 222.5 | +2.3 |
| 706.47 | 30.10 | 172.3 | 160.2 | +1.1 |

Table AI. *(Continued)*

| $T$ (K) | $P$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\lambda$ ($mW \cdot m^{-1} \cdot K^{-1}$) | $\delta$ (%) |
|---|---|---|---|---|
| 706.35 | 24.90 | 119.0 | 117.4 | +1.0 |
| 705.22 | 20.08 | 85.0 | 92.5 | −1.4 |
| 704.61 | 15.00 | 57.2 | 76.8 | −2.8 |
| 704.40 | 10.04 | 35.2 | 67.3 | −3.4 |
| 708.33 | 9.80 | 33.9 | 67.0 | −3.7 |
| 704.33 | 0.95 | 3.0 | 59.0 | −0.3 |
| 728.39 | 76.10 | 539.6 | 420.0 | +1.0 |
| 728.40 | 75.00 | 535.6 | 417.8 | +1.3 |
| 728.34 | 70.10 | 516.4 | 403.5 | +1.5 |
| 728.65 | 65.20 | 492.8 | 388.8 | +2.5 |
| 728.80 | 60.00 | 462.9 | 365.3 | +2.4 |
| 729.64 | 55.00 | 424.1 | 335.7 | +2.2 |
| 729.72 | 50.00 | 377.1 | 304.9 | +3.0 |
| 729.78 | 46.00 | 330.1 | 272.7 | +3.1 |
| 729.75 | 44.00 | 304.1 | 256.4 | +3.7 |
| 729.68 | 42.00 | 277.3 | 236.3 | +3.2 |
| 729.49 | 40.00 | 250.8 | 217.3 | +3.2 |
| 728.86 | 35.10 | 192.0 | 170.8 | +2.0 |
| 728.21 | 30.00 | 143.5 | 131.8 | 0.0 |
| 727.66 | 25.00 | 106.7 | 106.2 | −1.0 |
| 727.08 | 20.10 | 78.2 | 88.4 | −2.9 |
| 726.58 | 14.93 | 53.4 | 76.8 | −2.9 |
| 726.28 | 10.04 | 33.5 | 68.6 | −3.8 |
| 726.04 | 5.04 | 15.9 | 64.4 | −1.7 |
| 726.35 | 2.53 | 7.7 | 61.7 | −2.2 |
| 726.35 | 0.97 | 2.9 | 60.9 | −1.5 |
| 783.81 | 94.50 | 492.2 | 386.3 | +6.4 |
| 784.29 | 90.20 | 476.2 | 373.6 | +6.5 |
| 785.34 | 80.00 | 431.6 | 337.4 | +6.3 |
| 785.70 | 70.20 | 378.9 | 298.6 | +6.5 |
| 785.10 | 60.00 | 312.5 | 251.1 | +6.0 |
| 784.36 | 50.25 | 240.5 | 199.1 | +4.3 |
| 783.18 | 39.80 | 167.6 | 145.4 | +0.3 |
| 782.97 | 35.00 | 138.3 | 126.8 | −0.5 |
| 782.36 | 30.00 | 111.5 | 110.4 | −1.6 |
| 781.80 | 25.00 | 87.6 | 97.6 | −2.3 |
| 781.44 | 20.10 | 66.7 | 87.4 | −3.3 |
| 781.18 | 10.06 | 30.3 | 74.0 | −3.3 |
| 781.22 | 0.98 | 2.7 | 68.5 | −0.2 |

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