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THERMAL LINEAR EXPANSION OF NINE SELECTED AISI STAINLESS STEELS

By

P. D. Desai and C. Y. Ho

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Prepared for

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This technical report reviews the available experimental data and information on the thermal linear expansion of nine AISI stainless steels and presents the recommended values from 10 K to near the melting point of the stainless steels. The nine selected stainless steels are AISI 303, 304, 304L, 316, 317, 321, 347, 410, and 430. The recommended values include the percent thermal linear expansion, the instantaneous coefficient, and the mean coefficient of thermal linear expansion. These values are generated as a result of critical evaluation, analysis, and synthesis of the available data

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PREFACE

This technical report was prepared by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, for the American Iron and Steel Institute (AISI), Washington, D.C., under AISI Project Number 67-371 entitled "Thermal and Electrical Properties of Steels". This project has been under the technical direction of AISI Panel on Physical, Electrical and Magnetic Properties with Dr. C. A. Beiser as Chairman of the Panel and with Dr. G. L. Houze, Member of the Panel, being the designated point of contact on technical matters.

The initial scope of the project is to establish the best values of the electrical resistivity, thermal conductivity, and thermal expansion of nine selected AISI stainless steels over a wide range of temperatures. This is the second technical report to AISI which presents the results on the thermal expansion. The results on the electrical resistivity and the thermal conductivity of the nine selected AISI stainless steels have already been presented in the first technical report (CINDAS Report 45).

It is hoped that this work will prove useful not only to the iron and steel industry and to engineers and scientists specializing in the field but also to other engineering research and development programs and for applications in other industries, as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is thought that the critical evaluation, analysis and synthesis of data and the reference data generation constitute a unique aspect of this work.

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April 1978

ABSTRACT

This technical report reviews the available experimental data and information on the thermal linear expansion of nine AISI stainless steels and presents the recommended values from 10 K to near the melting point of the stainless steels. The nine selected stainless steels are AISI 303, 304, 304L, 316, 317, 321, 347, 410, and 430. The recommended values include the percent thermal linear expansion, the instantaneous coefficient, and the mean coefficient of thermal linear expansion. These values are generated as a result of critical evaluation, analysis, and synthesis of the available data and information. Data are synthesized for those stainless steels and temperature values for which no data are available. General background information on the stainless steels is given. The techniques of data evaluation, analysis, and synthesis used in the generation of recommended values is outlined.

CONTENTS

I. INTRODUCTION

The primary objective of this study was to generate recommended values for the thermal linear expansion and its instantaneous and mean coefficient of seven of the 300 series and two of the 400 series of AISI stainless steels, which were selected primarily because of their current technological and commercial importance.

The nine selected AISI stainless steels and their chemical composition ranges and limits are given in the following table.

Chemical Composition Ranges and Limits of
Nine Selected AISI Stainless Steels

AISI No.	Chemical Composition Ranges and Limits, Percent								
	C	Mn Max.	P Max.	S Max.	Si Max.	Cr	Ni	Mo	Other Elements
303	0.15 Max.	2.00	0.20	0.15 Min.	1.00	17.00/ 19.00	8.00 10.00	0.60* Max.	
304	0.08 Max.	2.00	0.045	0.030	1.00	18.00/ 20.00	8.00/ 10.50		
304L	0.030 Max.	2.00	0.045	0.030	1.00	18.00/ 20.00	8.00/ 12.00		
316	0.08 Max.	2.00	0.045	0.030	1.00	16.00/ 18.00	10.00/ 14.00	2.00/ 3.00	
317	0.08 Max.	2.00	0.045	0.030	1.00	18.00/ 20.00	11.00/ 15.00	3.00/ 4.00	
321	0.08 Max.	2.00	0.045	0.030	1.00	17.00/ 19.00	9.00/ 12.00		Ti 5 x C Min.
347	0.08 Max.	2.00	0.045	0.030	1.00	17.00/ 19.00	9.00/ 13.00		Nb-Ta 10 x C Min.
410	0.15 Max.	1.00	0.040	0.030	1.00	11.50/ 13.50			
430	0.12 Max.	1.00	0.040	0.030	1.00	16.00/ 18.00			

*Optional.

General background information on the stainless steels is given in Section II.

The recommended values are generated through a process in which the available data are exhaustively searched, systematically compiled, critically evaluated, analyzed, and then synthesized. The techniques of data evaluation and analysis used in the generation of recommended values are outlined in Section III.

The recommended values for the thermal linear expansion of each of the nine selected stainless steels are presented in Section IV in both tabular and graphical forms. These values cover the temperature from 10 K to near the melting point. Stainless steels, unlike pure metals, do not have a sharp melting point. They undergo melting over a temperature range of 100-200 degrees. Moreover, extrapolation of the thermal linear expansion values in and above the melting region is meaningless. Thermal expansion in this temperature region is generally presented as a variation of density with temperature.

The recommended values for the austenitic 300-series stainless steels are for the quench-annealed state. In the cases of AISI 410 and 430 stainless steels, they are for oil-quenched, and air-cooled and annealed states respectively. In the majority of cases, the tabulated recommended values are given beyond the physically significant figures. This is done merely for retaining the smoothness of the tabulated values and should not be considered indicative of the degree of accuracy or uncertainty of the values. The uncertainty in the recommended values is always explicitly stated.

Discussion text for each stainless steel provides information on the special features of that steel, the available data on the thermal linear expansion, and the considerations involved in arriving at the recommended values. Wherever possible, the effects of cold working on the thermal linear expansion are discussed individually in the text.

Conclusions of the present study are given in Section V. The complete bibliographic citations for the 30 references, which include all the major references on which the recommended values are based, are given in Section VI.

In this work, the recommended values are given for the percent thermal linear expansion, $\Delta L/L_0(\%)$, the instantaneous coefficient of thermal linear expansion, α, and the mean coefficient of thermal linear expansion, α_m. These are defined as

$$\frac{\Delta L}{L_0}\,(\%) = \frac{L_T - L_0}{L_0} \times 100$$

$$\alpha = \frac{d}{d_T}\left(\frac{\Delta L}{L_0}\right) = \frac{1}{L_0}\frac{dL}{dT}$$

and

$$\alpha_m = \frac{L_T - L_0}{L_0(T - T_0)}$$

where L_T and L_0 are lengths of the material (or lattice parameters) at temperature T and at 293 K, respectively.

The thermal expansion of a solid which exhibits a phase transition has a discontinuity (AISI 410 and 430 stainless steels) in the vicinity of the transition, at which the expansion coefficient is momentarily infinite.

II. GENERAL BACKGROUND

In practical applications stainless steels are chosen mainly for their most important property - corrosion resistance. Other service requirements and properties may then become important after a stainless steel with the desired corrosion resistance has been chosen. In general, the chemical composition, the heat treatment, and the cold-work state are the major factors that determine the various properties of the steels. These will be discussed briefly below, with emphasis on their effects on the thermal linear expansion.

The corrosion-resistant property of stainless steels is achieved by the addition of chromium, in excess of 12%, to iron. Thus chromium is the major alloying element in all stainless steels. In the 300 series stainless steels, the chromium content is about 18%. Nickel, which is usually present at about 8-12% in the 300 series stainless steels, serves to stabilize the austenite. The fourth abundant element is manganese (≤2%), which also tends to stabilize the austenite. Manganese in the sulfide form also improves the hot workability and the machinability. Silicon usually appears as trace impurity (≤1%), though it might improve the corrosion resistance to a limited extent. Other elements are added to acquire certain desired properties for special service requirements. The 400 series stainless steels differ from the 300 series by the complete absence of nickel. Their structures also differ from that of the austenite, and may be ferritic or martensitic depending on the chromium concentration.

In the 300 series stainless steels, heat-treatments are very limited. In order to maintain these steels in the metastable austenitic condition, they are invariably quench-annealed from about 1300 K (1900°F) and perhaps stressed-relieved by heating up to ~700 K (800°F). AISI 430 stainless steel is ferritic at all temperatures and its properties are therefore unchanged by heat treatments. On the other hand, AISI 410 stainless steel is subject to different heat treatments. This steel is martensitic when oil-quenched or air-cooled from ≥1300 K (1850°F) and is ferritic when cooled slowly from 1050 K (1450°F) after annealing.

Cold work produces dislocations and metallurgical transformation in steels. In the austenitic stainless steels, there is a tendency to form martensite. The degree of transformation depends upon the deformation and on the type of steel. The effect of the cold working on the thermal linear expansion is discussed individually for each stainless steel and in greater length for AISI 304 stainless steel.

III. DATA EVALUATION AND GENERATION OF RECOMMENDED VALUES

Due to the difficulties of measuring accurately the properties of materials and of adequately characterizing the test specimens, especially solids, the property data available from the scientific and technical literature are often conflicting, widely diverging, and subject to large uncertainty. Indiscriminate use of literature data for engineering design calculations without knowing their reliability is dangerous and may cause inefficiency or product failure, which at times can be disastrous. Therefore, it is imperative to evaluate critically the validity, reliability, and accuracy of the literature data and related information, to resolve and reconcile the disagreements in conflicting data, and to synthesize often fragmentary data in order to generate a full range of internally consistent recommended values.

In the critical evaluation of the validity and reliability of a particular set of experimental data, the temperature dependence of the data is examined and any unusual dependence or anomaly is carefully investigated. The experimental technique is reviewed to see whether the actual boundary conditions in the measurement agreed with those assumed in the theory. The reduction of data is examined to see whether all the necessary corrections were appropriately applied. The estimation of experimental inaccuracies is checked to ensure that all the possible sources of error, particularly systematic error, were considered by the author(s). Experimental data could be judged to be reliable only if all sources of systematic error were eliminated or minimized and accounted for. Major sources of systematic error include unsuitable experimental method, poor experimental technique, poor instrumentation and poor sensitivity of measuring devices, sensors, or circuits, specimen and/or thermocouple contamination, and the mismatch between actual experimental boundary conditions and those assumed in the theoretical model used to define and derive the value of the property. These and other possible sources of errors are carefully considered in critical evaluation and analysis of experimental data. The uncertainty of a set of data depends, however, not only on the estimated inaccuracy of the data, but also on the inadequacy of characterization of the material for which the data are reported.

In many cases, however, research papers do not contain adequate information for a data evaluator to perform a truly critical evaluation. In these cases, some other considerations may have to be used for data evaluation. For instance, if several authors' data agree with one another and, more importantly, these were obtained by using different experimental methods, these data are likely to be reliable. However, if the data were observed by using the same experimental method, even though they all agree, the reliability of the data is still subject to questioning, because they may all suffer from a common, but unknown source of error. Secondly, if the same apparatus has been used for measurements of other materials and the results are reliable, and if the result of measurement on the new material is in the same range, the result for the new material is likely to be reliable. However, if the information given by the author is entirely inadequate to make any value judgment, the data assessment becomes subjective. At times judgments may be based upon factors and considerations such as the purpose and motivation for the measurement, general knowledge of the experimenter, his past performance, the reputation of his laboratory, etc.

In the process of critical evaluation of experimental data outlined above, unreliable and erroneous data are uncovered and eliminated from further consideration. The remaining evaluated data are then subjected to further analysis and correlation in regard to the various factors that affect the property under study. In the cases where available data are scarce, estimated values can be synthesized by theoretical considerations and by semiempirical techniques such as intercomparing the property values of various stainless steels (both domestic and foreign) of similar chemical compositions and metallurgical structures accounting for the various affecting factors.

Thus, the recommended values of $\Delta L/L_0(\%)$ are generated by the method outlined above. The values of the mean coefficient of thermal linear expansion (α_m) are calculated from the $\Delta L/L_0(\%)$ values. The values of the instantaneous coefficient of thermal linear expansion are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values. The resulting values are sometimes adjusted slightly in order to be consistent with the general shape of the recommended thermal expansion curve and with those reported by individual investigators.

IV. THERMAL LINEAR EXPANSION OF SELECTED AISI STAINLESS STEELS

1. AISI 303 Stainless Steel

AISI 303 stainless steel, which is a modification of the basic 18-8 austenitic stainless steel, contains higher amounts of phosphorous (0.20% max) and sulfur (0.15% min.). The high sulfur content makes it more machinable and possibly improves its ductility. The other variation of this steel is AISI 303Se stainless steel. This contains selenium (0.15%) which is added for the same reason given above. Since these elements are present in relatively small quantities (≤0.20%), the thermal expansion of these steels are very close to that of the more common type, AISI 304, although their mechanical properties are quite different.

There are only two data sets available for the thermal linear expansion of this steel [1,2]. One data set is for temperatures below 293 K [1] and the other covers the temperature range 293-832 K [2]. The percent thermal linear expansion values below 293 K of this steel are close to those of AISI 304 stainless steel (see next section) and furthermore, the composition of these two steels are quite similar. It can be concluded that the variation of the thermal linear expansion due to the small difference in composition between AISI 303 and 304 is negligible and that the recommended percent thermal linear expansion values for AISI 304 stainless steel which are well established and reported in the next section are applicable also to AISI 303 and 303Se stainless steels.

The values of the mean coefficient of thermal linear expansion are calculated from the percent linear expansion values. The values of the instantaneous coefficient are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the thermal expansion curve.

The recommended values are tabulated in Table 1 and shown in Figure 1. The uncertainty in the values of the thermal linear expansion, the mean coefficient, and the instantaneous coefficient is within ±5%, ±5%, and ±10%, respectively.

Table 1. Thermal Linear Expansion of AISI 303 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.338	1.10	11.94
20	-0.334	7.85	12.23
30	-0.325	8.72	12.36
40	-0.316	9.31	12.49
50	-0.307	9.78	12.63
60	-0.297	10.17	12.75
70	-0.286	10.49	12.83
80	-0.276	10.80	12.96
90	-0.265	11.09	13.05
100	-0.254	11.39	13.16
150	-0.194	12.38	13.57
200	-0.130	13.22	13.98
250	-0.062	14.05	14.37
273	-0.029	14.38	14.57
293	0.000	14.71	---
300	0.010	14.90	14.78
350	0.086	15.60	15.18
400	0.167	16.27	15.61
500	0.338	17.50	16.33
600	0.519	18.58	16.91
700	0.709	19.49	17.42
800	0.907	20.20	17.89
900	1.112	20.69	18.32
1000	1.323	21.04	18.71
1100	1.536	21.25	19.03
1200	1.748	21.36	19.27
1300	1.959	21.40	19.45
1400	2.171	21.45	19.61
1500	2.386*	21.52*	19.77*
1600	2.601*	21.61*	19.90*
1670§	2.753*	21.69*	19.99*

* Extrapolated values.
† For the uncertainty in the recommended values, see text.
§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

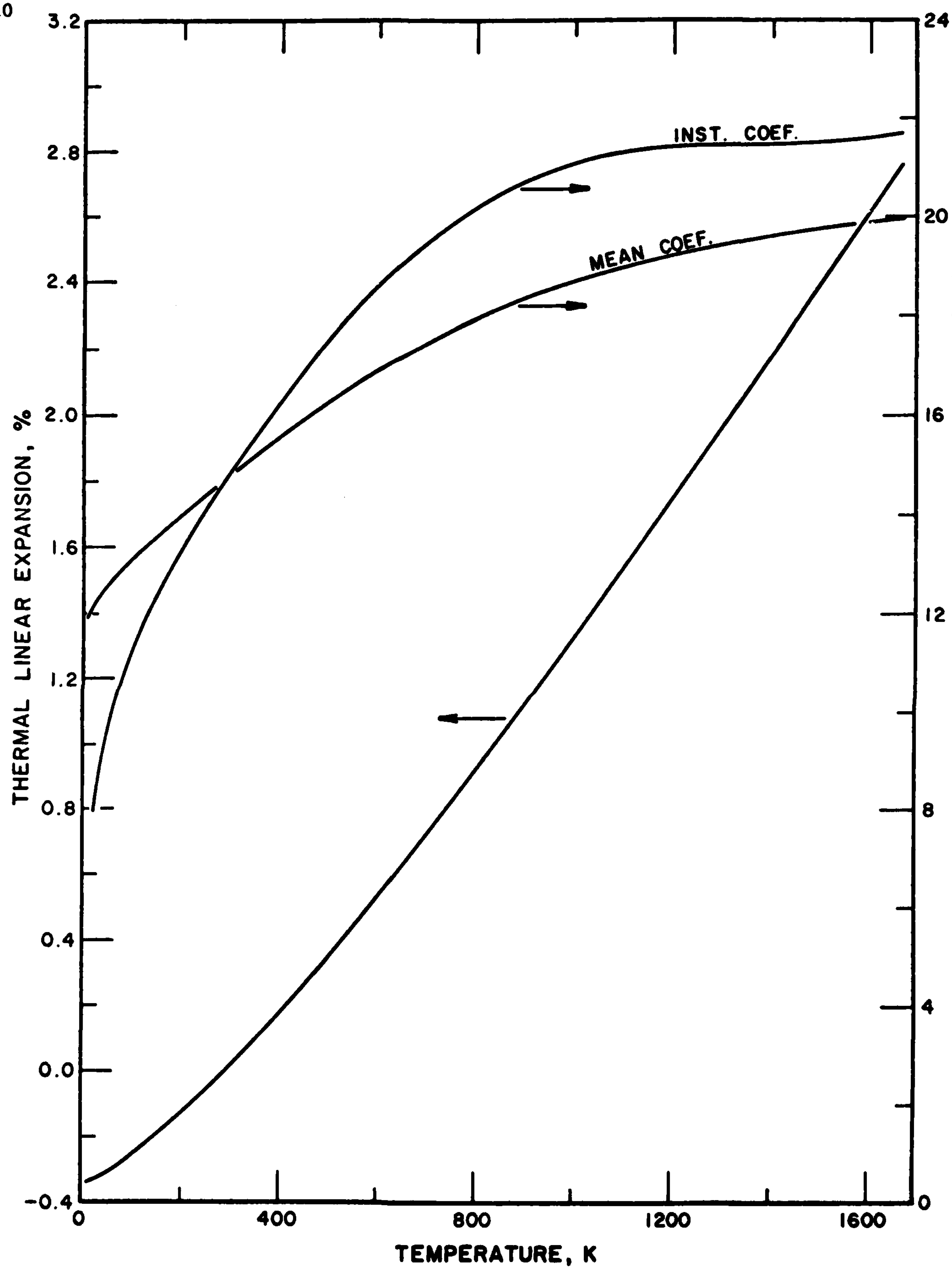

Figure 1. Thermal Linear Expansion of AISI 303 Stainless Steel

2. AISI 304 Stainless Steel

This is a low-carbon member of the 18-8 type austenitic stainless steel, with a slightly higher chromium content for improved corrosion resistance. This steel is susceptible to intergranular corrosion in the temperature range 700-1150 K (800-1600°F) due to carbide precipitation.

There are six data sets available for the thermal linear expansion of AISI 304 stainless steel. Among these, one data set [3] is for temperatures below 293 K and the remaining data sets [4-8] cover the temperature range 293-1400 K. The recommended percent thermal linear expansion values are derived from and agree well with the data reported by Furman [4], Valentich [5], Yaggee, Gilbert, and Styles [6], Martin and Weir [7], and Droege [8].

AISI 300 series stainless steels have a tendency to undergo martensitic transformation upon cold working. Severe cold working also produces dislocations. The amount of research on the effect of cold working is very small. It appears that in general cold working does not change the thermal expansion appreciably. However, in the case of severe cold working, the expansion decreases. One cannot quantitatively relate the degree of cold working to the change of thermal expansion. In general, cold working initially has almost no effect, additional cold working will have a large effect and then further cold working will have little effect.

The values of the mean coefficient of thermal linear expansion are calculated from the percent thermal linear expansion values. The values of the instantaneous coefficient of thermal linear expansion are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the thermal expansion curve.

The recommended values are tabulated in Table 2 and shown in Figure 2. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5%, and that of the instantaneous coefficient is within ±10%.

Table 2. Thermal Linear Expansion of AISI 304 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.338	1.10	11.94
20	-0.334	7.85	12.23
30	-0.325	8.72	12.36
40	-0.316	9.31	12.49
50	-0.307	9.78	12.63
60	-0.297	10.17	12.75
70	-0.286	10.49	12.83
80	-0.276	10.80	12.96
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900	1.112	20.69	18.32
1000	1.323	21.04	18.71
1100	1.536	21.25	19.03
1200	1.748	21.36	19.27
1300	1.959	21.40	19.45
1400	2.171	21.45	19.61
1500	2.386*	21.52*	19.77*
1600	2.601*	21.61*	19.90*
1670§	2.753*	21.69*	19.99*

* Extrapolated values.
† For the uncertainty in the recommended values, see text.
§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

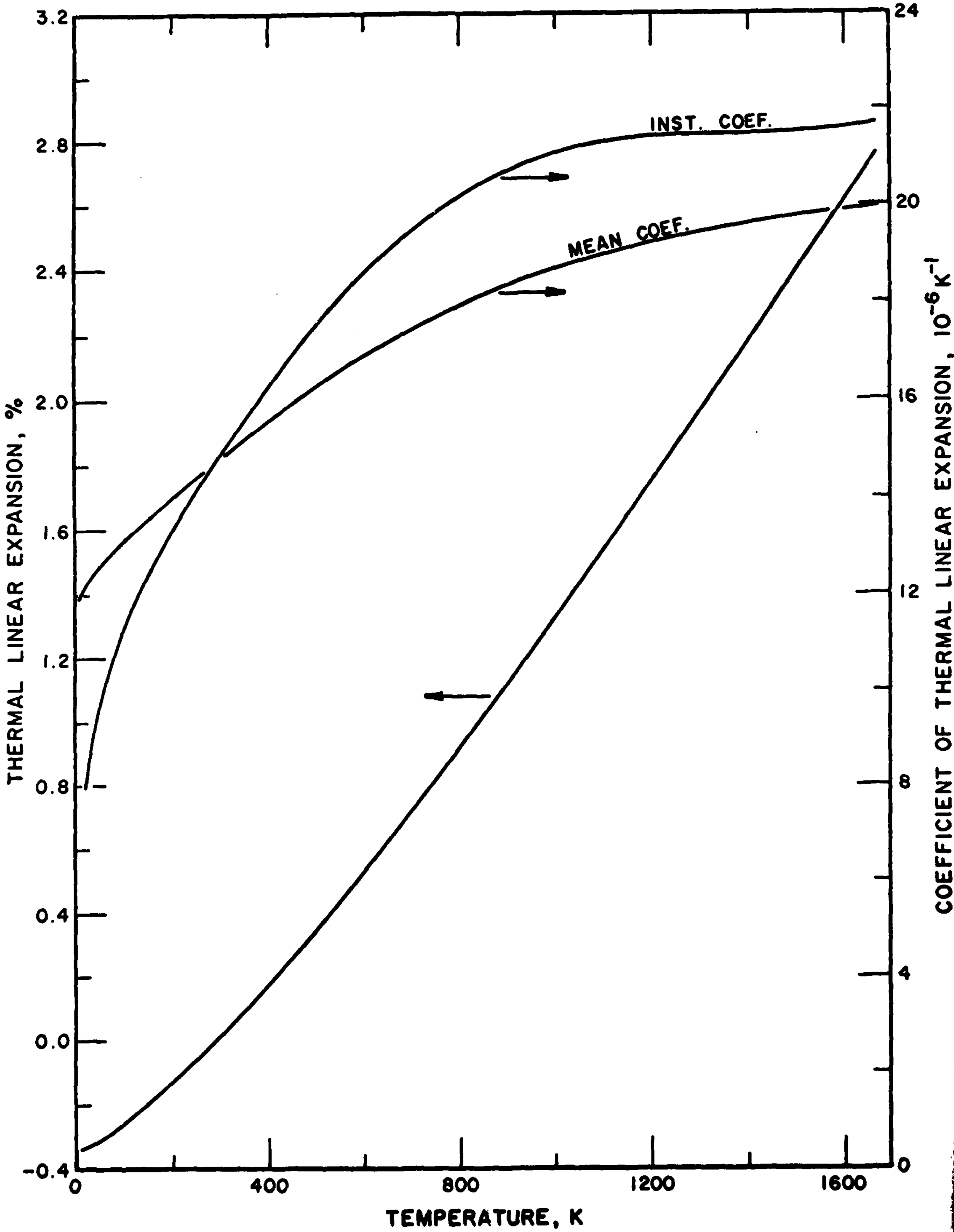

Figure 2. Thermal Linear Expansion of AISI 304 Stainless Steel

3. AISI 304L Stainless Steel

This is a low carbon version of AISI 304 stainless steel. The reduced carbon content improves its resistance to intragranular corrosion.

There are three data sets available for the thermal linear expansion of this steel. Among these, one data set [9] is for temperatures above 293 K and the other two data sets [1,10] are below 293 K. The small difference in carbon content between this steel and AISI 304 stainless steel is judged to be insignificant in altering the thermal linear expansion values. Therefore, the values of the percent thermal linear expansions and of the coefficients recommended for AISI 304 stainless steel are applicable also to this steel. The recommended values agree well with the low-temperature data reported by Arp, et al. [1] and by NASA [10]. The high-temperature data reported by Conway and Flagella [9] agree also well except that they are about 8% higher above 800 K.

The recommended values are tabulated in Table 3 and shown in Figure 3 for the sake of completeness. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5%, and that of the instantaneous coefficient is within ±10%.

Table 3. Thermal Linear Expansion of AISI 304L Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.338	1.10	11.94
20	-0.334	7.85	12.23
30	-0.325	8.72	12.36
40	-0.316	9.31	12.49
50	-0.307	9.78	12.63
60	-0.297	10.17	12.75
70	-0.286	10.49	12.83
80	-0.276	10.80	12.96
90	-0.265	11.09	13.05
100	-0.254	11.39	13.16
150	-0.194	12.38	13.57
200	-0.130	13.22	13.98
250	-0.062	14.05	14.37
273	-0.029	14.38	14.57
293	0.000	14.71	---
300	0.010	14.90	14.78
350	0.086	15.60	15.18
400	0.167	16.27	15.61
500	0.338	17.50	16.33
600	0.519	18.58	16.91
700	0.709	19.49	17.42
800	0.907	20.20	17.89
900	1.112	20.69	18.32
1000	1.323	21.04	18.71
1100	1.536	21.25	19.03
1200	1.748	21.36	19.27
1300	1.959	21.40	19.45
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1500	2.386*	21.52*	19.77*
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* Extrapolated values.
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§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

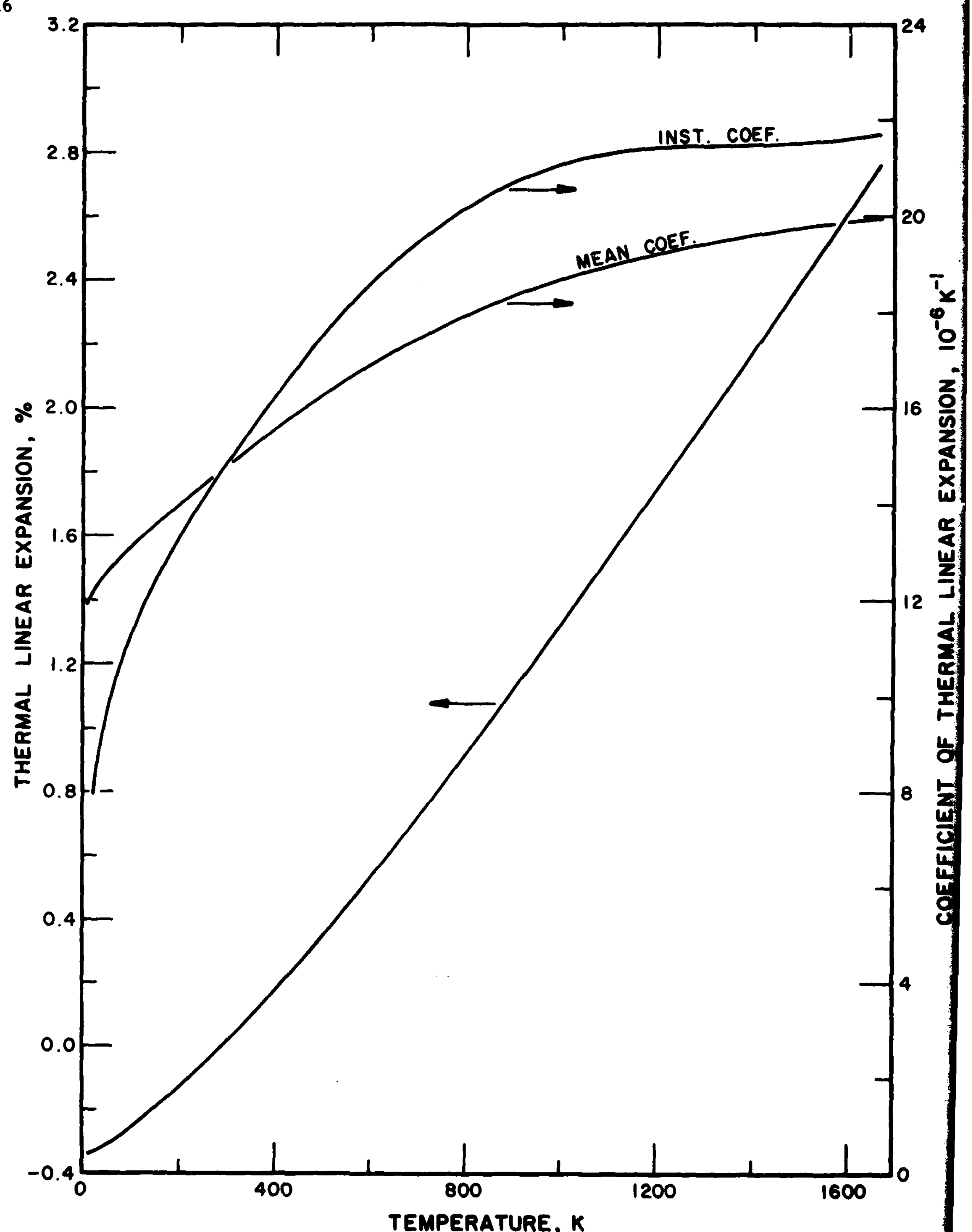

Figure 3. Thermal Linear Expansion of AISI 304L Stainless Steel

4. AISI 316 Stainless Steel

AISI 316 stainless steel is one of the two* most stable austenitic stainless steels because of its higher nickel and molybdenum content. It contains 2-3% molybdenum which improves its corrosion resistance and mechanical strength, especially at elevated temperatures. However, just because of its molybdenum content, formation of the brittle sigma phase at grain boundaries may take place after prolonged service at elevated temperatures.

There are eight sets of experimental data available for the thermal linear expansion covering the temperature range 19-1616 K [4,6,10,12-16]. The recommended values for AISI 316 stainless steel are derived from the data reported by Furmen [4], NASA [10], Lucks and Deem [12], Lucks, et al. [13], and Arthur and Coulson [15]. The data reported by Fieldhouse, Hedge, and Lang [14] are about 5-15% higher than the recommended values and those reported by Yaggee, Gilbert, and Styles [6] and by Yaggee and Styles [11] are about 5% lower.

AISI 316 stainless steel has shown very little tendency for martensitic transformation. Hence, thermal linear expansion is not expected to change substantially by cold working.

The values of the mean coefficient of thermal linear expansion are calculated from the percent linear expansion values. The values of the instantaneous coefficient are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with the resulting values slightly adjusted in order to be consistent with the general shape of the thermal expansion curve.

The recommended values are tabulated in Table 4 and shown in Figure 4. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5%, and that of the instantaneous coefficient is within ±10%.

*The other is AISI 317 stainless steel.

Table 4. Thermal Linear Expansion of AISI 316 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.326	0.40	11.48
20	-0.325	1.90	11.90
30	-0.322	3.70	12.24
40	-0.317	6.00	12.53
50	-0.310	7.56	12.76
60	-0.302	8.68	12.96
70	-0.293	9.50	13.14
80	-0.283	10.16	13.29
90	-0.273	10.70	13.45
100	-0.262	11.20	13.58
150	-0.202	12.68	14.13
200	-0.136	13.76	14.62
250	-0.065	14.66	15.07
273	-0.030	15.06	15.24
293	0.000	15.40	---
300	0.011	15.50	15.44
350	0.090	16.20	15.80
400	0.173	16.89	16.17
500	0.348	18.06	16.81
600	0.533	19.03	17.36
700	0.727	19.80	17.86
800	0.928	20.36	18.30
900	1.133	20.76	18.67
1000	1.342	20.97	18.98
1100	1.552	21.13	19.23
1200	1.764	21.25	19.45
1300	1.977	21.34	19.63
1400	2.191	21.41	19.79
1500	2.405	21.44	19.93
1600	2.615	21.48	20.01
1644§	2.705	21.49	20.02

† For the uncertainty in the recommended values, see text.
§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

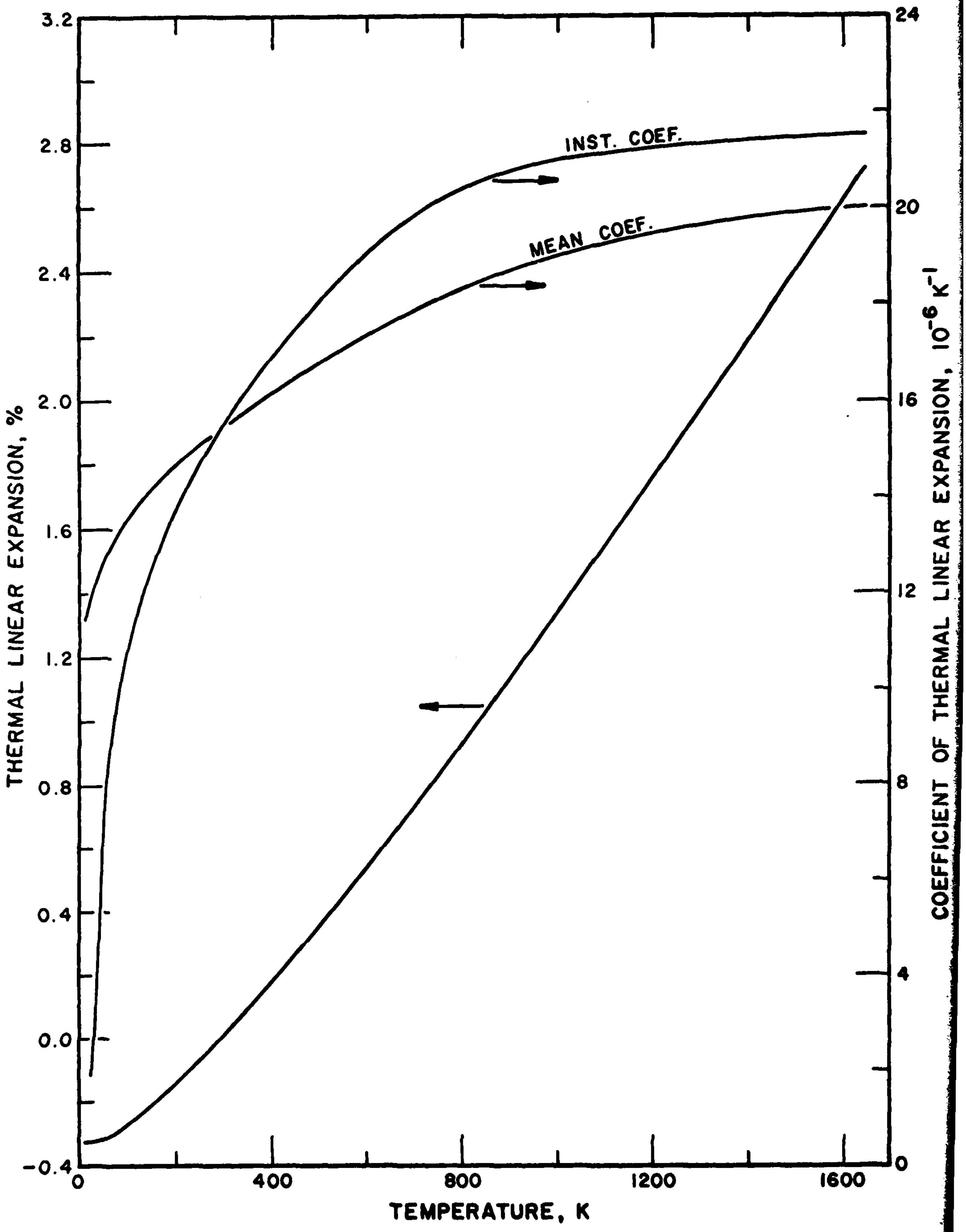

Figure 4. Thermal Linear Expansion of AISI 316 Stainless Steel

5. AISI 317 Stainless Steel

Because of its high molbydenum (3-4%) and nickel (11-15%) content, AISI 317 stainless steel is probably the most stable austenitic stainless steel. Its properties are almost identical with those of AISI 316 stainless steel.

No experimental data are available for the thermal linear expansion of this steel. The recommended values are taken from those recommended for AISI 316 stainless steel.

The effect of cold working on the thermal expansion of this steel is also most likely to be the same as that for AISI 316 stainless steel.

The recommended values are tabulated in Table 5 and shown in Figure 5. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5%, and that of the instantaneous coefficient is within ±10%.

Table 5. Thermal Linear Expansion of AISI 317 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.326	0.40	11.48
20	-0.325	1.90	11.90
30	-0.322	3.70	12.24
40	-0.317	6.00	12.53
50	-0.310	7.56	12.76
60	-0.302	8.68	12.96
70	-0.293	9.50	13.14
80	-0.283	10.16	13.29
90	-0.273	10.70	13.45
100	-0.262	11.20	13.58
150	-0.202	12.68	14.13
200	-0.136	13.76	14.62
250	-0.065	14.66	15.07
273	-0.030	15.06	15.24
293	0.000	15.40	---
300	0.011	15.50	15.44
350	0.090	16.20	15.80
400	0.173	16.89	16.17
500	0.348	18.06	16.81
600	0.533	19.03	17.36
700	0.727	19.80	17.86
800	0.928	20.36	18.30
900	1.133	20.76	18.67
1000	1.342	20.97	18.98
1100	1.552	21.13	19.23
1200	1.764	21.25	19.45
1300	1.977	21.34	19.63
1400	2.191	21.41	19.79
1500	2.405	21.44	19.93
1600	2.615	21.48	20.01
1644§	2.705	21.49	20.02

† For the uncertainty in the recommended values, see text.
§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

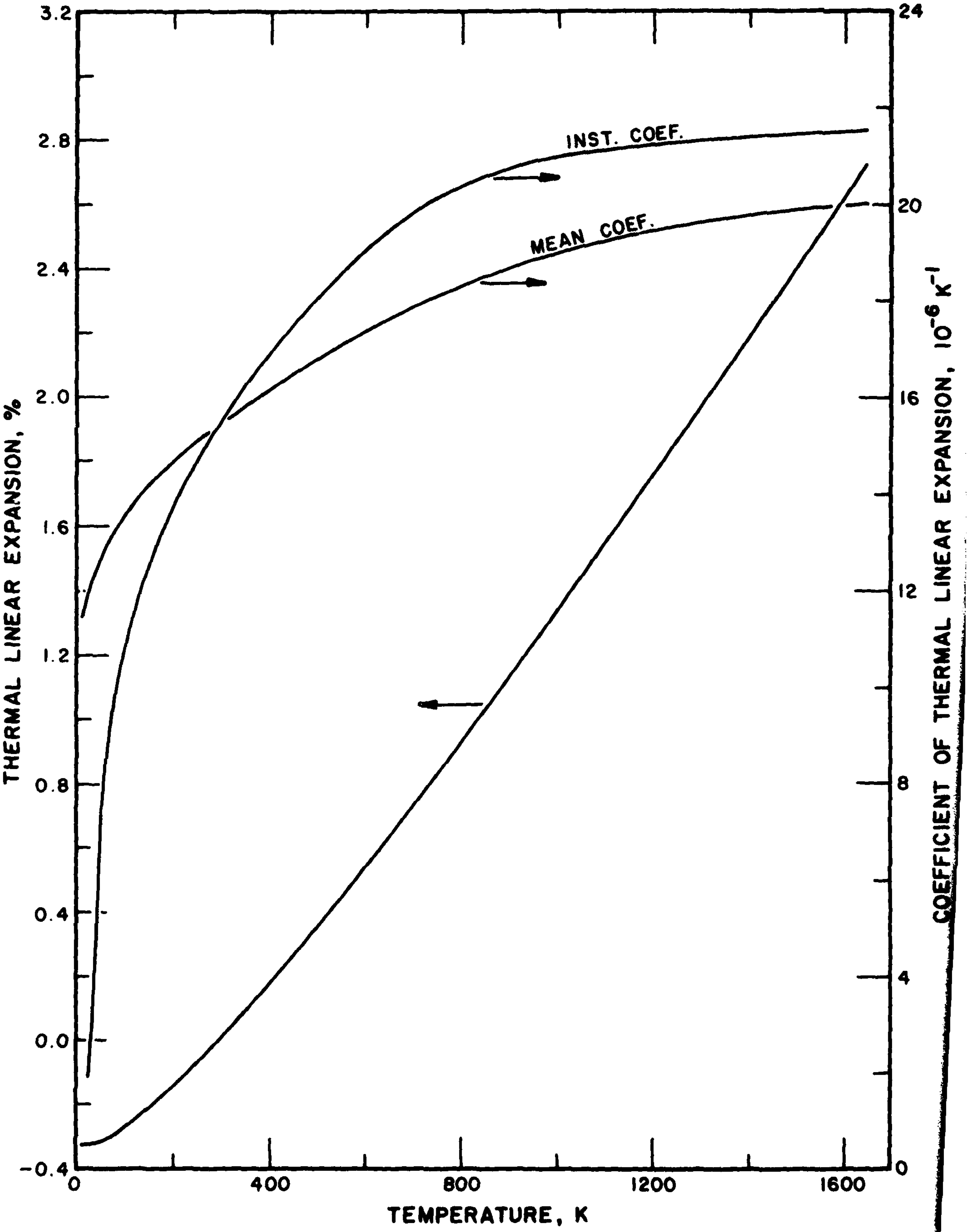

Figure 5. Thermal Linear Expansion of AISI 317 Stainless Steel

6. AISI 321 Stainless Steel

AISI 321 stainless steel is a carbide-stabilized modification of the basic 18-8 austenitic stainless steel. The carbide stabilization is achieved by adding titanium (5 x C Min.) to the steel. This steel is mostly used in welding applications where post-welding annealing is impractical. Due to the carbide stabilization, the probability of intergranular corrosion in the temperature range 700-1150 K (800-1600°F) is less.

There are six sets of experimental data [1,10,17-20] available for the thermal linear expansion of AISI 321 stainless steel. Among these, three data sets are for temperatures below 293 K [1,10,18]. The recommended percent thermal linear expansion values are based on the data reported by Arp, et al. [1], NASA [10], Seibel and Mason [16], Crane, Lovell, and Johnson [17], Horton, Smith, and Ruff [18], and Totskii [19]. The data reported by Totskii [19] is for 1Kh18N9T steel which is a Russian equivalent of AISI 321 stainless steel. In deciding the slope of the thermal linear expansion curve at 293 K, more weight was given to the low-temperature data [1,10,18].

The values of the mean coefficient of thermal linear expansion are calculated from the percent linear expansion values. The values of the instantaneous coefficient are obtained by differentiation of empirical equations which are used to fit the thermal linear expansion values, with resulting values slightly adjusted in order to be consistent with the general shape of the thermal expansion curve.

The recommended values are tabulated in Table 6 and shown in Figure 6. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5%, and that of the instantaneous coefficient is within ±10%.

Table 6. Thermal Linear Expansion of AISI 321 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.325	0.38	11.48
20	-0.325	0.94	11.90
30	-0.323	1.70	12.28
40	-0.321	2.70	12.69
50	-0.317	4.00	13.04
60	-0.313	5.50	13.43
70	-0.307	6.82	13.77
80	-0.299	8.34	14.04
90	-0.290	9.75	14.29
100	-0.280	10.86	14.51
150	-0.217	13.80	15.17
200	-0.145	14.90	15.59
250	-0.068	15.62	15.91
273	-0.032	15.89	16.01
293	0.000	16.17	---
300	0.011	16.21	16.18
350	0.093	16.50	16.32
400	0.176	16.81	16.44
500	0.347	17.34	16.76
600	0.523	17.81	17.04
700	0.703	18.18	17.27
800	0.886	18.48	17.47
900	1.073	18.75	17.68
1000	1.261	18.98	17.84
1100	1.452	19.17	17.99
1200	1.645	19.35	18.14
1300	1.839	19.50	18.26
1400	2.035	19.70	18.38
1500	2.233	19.90	18.50
1600	2.433	20.12	18.62
1672§	2.582	20.30	18.72

† For the uncertainty in the recommended values, see text.
§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

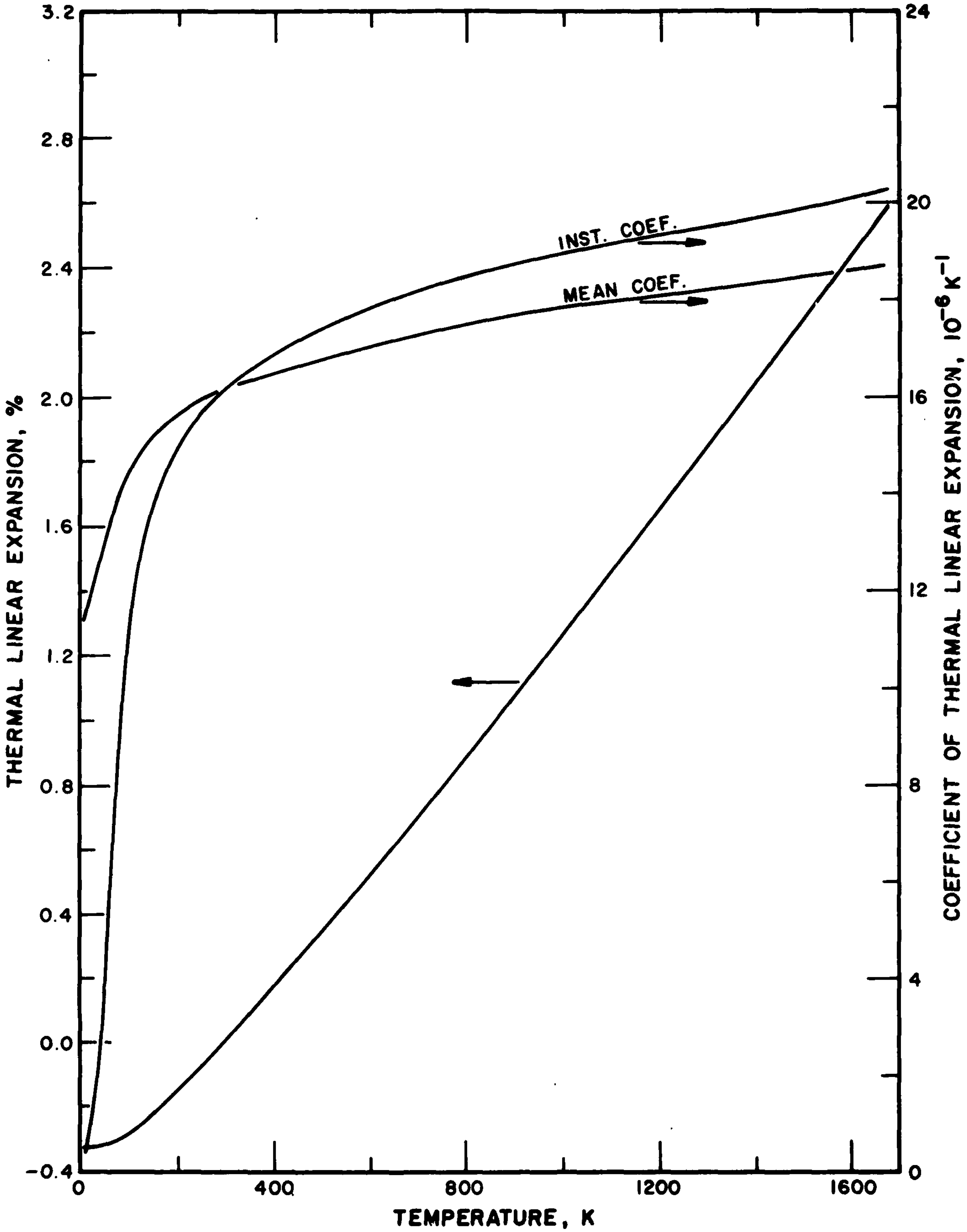

Figure 6. Thermal Linear Expansion of AISI 321 Stainless Steel

7. AISI 347 Stainless Steel

AISI 347 stainless steel is another carbide-stabilized austenitic stainless steel. Niobium and sometimes tantalum (Nb-Ta 10 x C Min.) are used as stabilizing elements. Its applications and properties are fairly close to those of AISI 321 stainless steel, except that AISI 347 stainless steel has a better stability because niobium does not oxidize as easily as titanium does.

There are thirteen sets of experimental data available for the thermal linear expansion of AISI 347 stainless steel [1,4,5,10,12-15,18,20-22]. The temperature range covered by these data sets is 18-1494 K. The recommended values of the percent thermal linear expansion for AISI 347 stainless steel agree well with the data reported by Arp, et al. [1], Furman [4], NASA [10], Lucks and Deem [12], and Lucks, et al. [13]. The data reported by Valentich [5], Horton, Smith, and Ruff [18], Aerojet Corporation [20], and Watrous [22] are about 4-10% lower and those reported by Fieldhouse, Hedge, and Lang [14] and Rhodes, et al. [21] are about 4% and 5-25% respectively higher than the recommended values.

The values of the mean coefficient of thermal linear expansion are calculated from the percent linear expansion values. The values of the instantaneous coefficient are obtained by differentiation of empirical equations which are used to fit the thermal expansion data, with resulting values slightly adjusted in order to be consistent with the general shape of the thermal expansion curve. The values of the instantaneous coefficient reported by Arthur and Coulson [15] are about 6-10% lower than the recommended values.

The recommended values are tabulated in Table 7 and shown in Figure 7. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5%, and that of the instantaneous coefficient is within ±10%.

Table 7. Thermal Linear Expansion of AISI 347 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.315	0.30	11.13
20	-0.315	0.69	11.54
30	-0.314	1.16	11.94
40	-0.313	1.80	12.37
50	-0.311	2.68	12.80
60	-0.307	4.54	13.18
70	-0.301	6.69	13.50
80	-0.294	8.40	13.80
90	-0.285	9.70	14.04
100	-0.275	10.69	14.25
150	-0.214	13.35	14.97
200	-0.143	14.68	15.38
250	-0.068	15.48	15.81
273	-0.032	15.81	16.00
293	0.000	16.11	---
300	0.011	16.19	16.14
350	0.094	16.80	16.49
400	0.179	17.36	16.73
500	0.358	18.35	17.29
600	0.545	19.18	17.75
700	0.741	19.89	18.21
800	0.942	20.44	18.58
900	1.149	20.84	18.93
1000	1.358	21.09	19.21
1100	1.570	21.26	19.45
1200	1.783	21.37	19.65
1300	1.998	21.48	19.84
1400	2.213	21.55	19.99
1500	2.429	21.61	20.12
1600	2.645*	21.64*	20.24*
1672§	2.801*	21.66*	20.31*

* Extrapolated values.
† For the uncertainty in the recommended values, see text.
§ Solidus temperature.
¶ Mean coefficient from 293 K to indicated temperature.

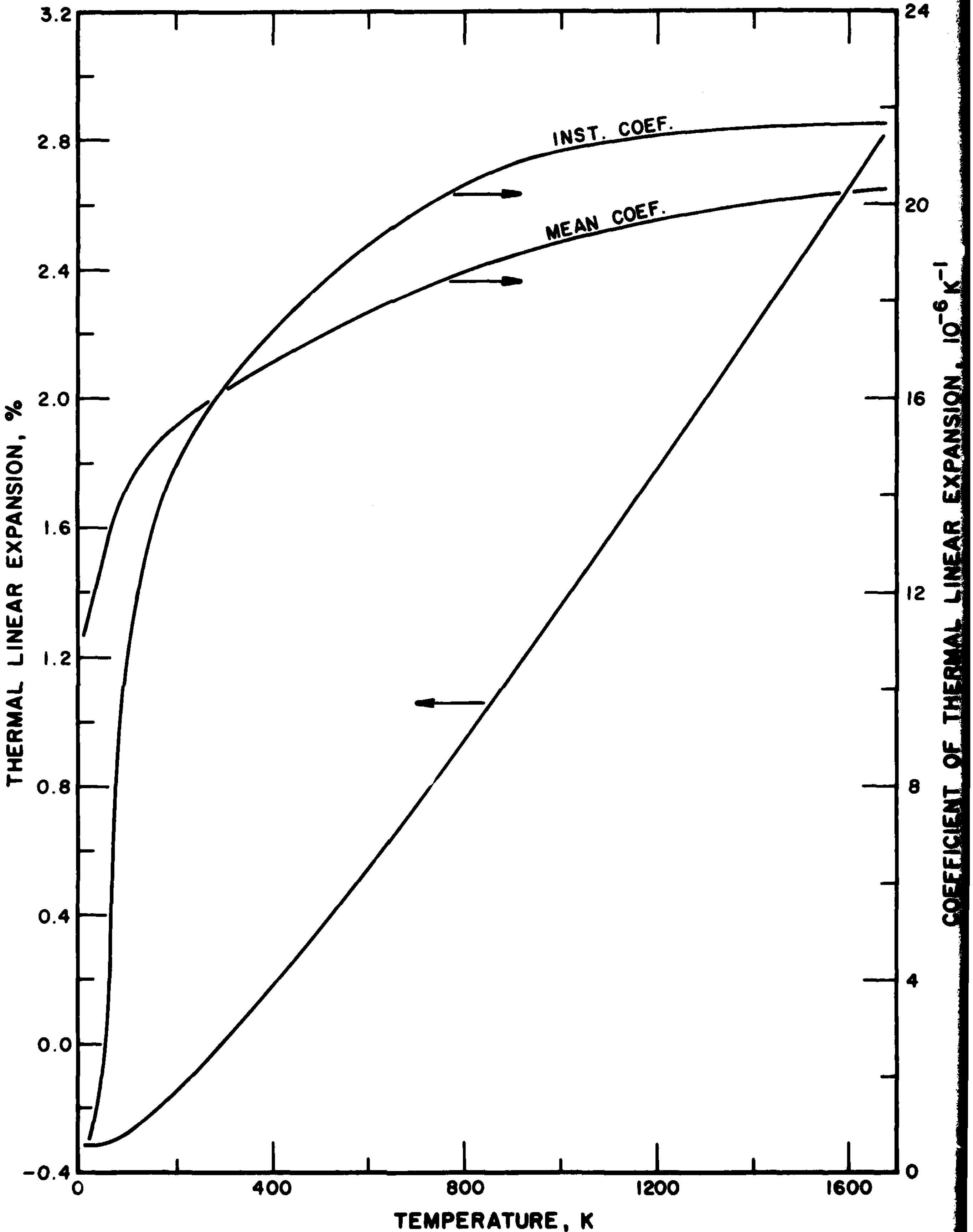

Figure 7. Thermal Linear Expansion of AISI 347 Stainless Steel

8. AISI 410 Stainless Steel

AISI 410 stainless steel is austenitic at elevated temperatures and either ferritic or martensitic at room temperature because of its low chromium content and the absence of nickel. It is usually produced in the martensitic condition resulting from being quenched and tempered. It would become ferritic by fully annealing and slowly cooling. This steel is susceptible to temper embrittlement in the temperature range 700-800 K (750-950°F). Therefore, services of this steel at these temperatures should be avoided. This stainless steel is a low cost general purpose steel of wide commercial applications, but it is inferior to the austenitic stainless steels in corrosion resistance due to its low chromium content.

There are twelve sets of experimental data available for the thermal linear expansion of either AISI 410 stainless steel or steels with similar composition [21,23-29]. These data sets cover the temperature range 18-1195 K. The recommended values of the percent thermal linear expansion are derived from the data reported by Rhodes, et al. [21], Johnston, Altman, and Rubin [23], Sander and Hidnert [24], Laquer [25], Lement and Averbach [26], and Shulga and Zamora [28]. A sudden drop in the percent thermal linear expansion values at 1125 K is due to the α-β transformation. The recommended values above 1125 K are based on the data reported by Sander and Hidnert [24]. Hysteresis effect in the thermal expansion values possibly due to the improper heating and cooling rates used are observed by Sander and Hidnert [24]. The tabulated values above 1200 K are extrapolated.

The values of the mean coefficient of thermal linear expansion are calculated from the recommended values of percent thermal linear expansion. The values of the instantaneous coefficient are primarily based on the data reported by Rhodes, et al. [21], Johnston, et al. [23], and Shulga and Zamora [28]. The values obtained by differentiations of empirical equations which are used to fit the thermal linear expansion values are used as a guide in determining the general shape of the curve.

There is no significant metallurgical transformation in this steel upon cold working. The thermal expansion is, therefore, not altered significantly by it.

The recommended values are tabulated in Table 8 and shown in Figure 8. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5% below 800 K and about ±10% above that temperature. The uncertainty in the instantaneous coefficient values is within ±15%.

Table 8. Thermal Linear Expansion of AISI 410 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.177	0.01	6.25
20	-0.177	0.05	6.48
30	-0.177	0.20	6.73
40	-0.177	0.50	7.00
50	-0.175	1.00	7.20
60	-0.174	1.65	7.47
70	-0.172	2.40	7.71
80	-0.169	3.15	7.93
90	-0.166	3.90	8.18
100	-0.162	4.55	8.39
150	-0.132	7.05	9.23
200	-0.092	8.85	9.89
250	-0.044	10.00	10.23
273	-0.021	10.37	10.50
293	0.000	10.65	---
300	0.008	10.72	10.70
350	0.062	11.22	10.95
400	0.119	11.58	11.12
500	0.238	12.08	11.50
600	0.362	12.43	11.80
700	0.488	12.80	12.00
800	0.618	13.10	12.20
900	0.748	13.30	12.32
1000	0.882	13.55	12.48
1100§	1.019	13.75	12.63
1100§	0.770	18.13	9.54
1150	0.862	19.07	10.06
1200	0.961	20.03	10.60
1250	1.065*	21.01*	11.13*
1300	1.170*	21.99*	11.62*
1350	1.282*	23.19*	12.13*
1400	1.396*	24.30*	12.61*
1450	1.520*	25.42*	13.14*
1500	1.660*	26.55*	13.75*

* Extrapolated values.
† For the uncertainty in the recommended values, see text.
§ α-γ phase transformation.
¶ Mean coefficient from 293 K to indicated temperature.

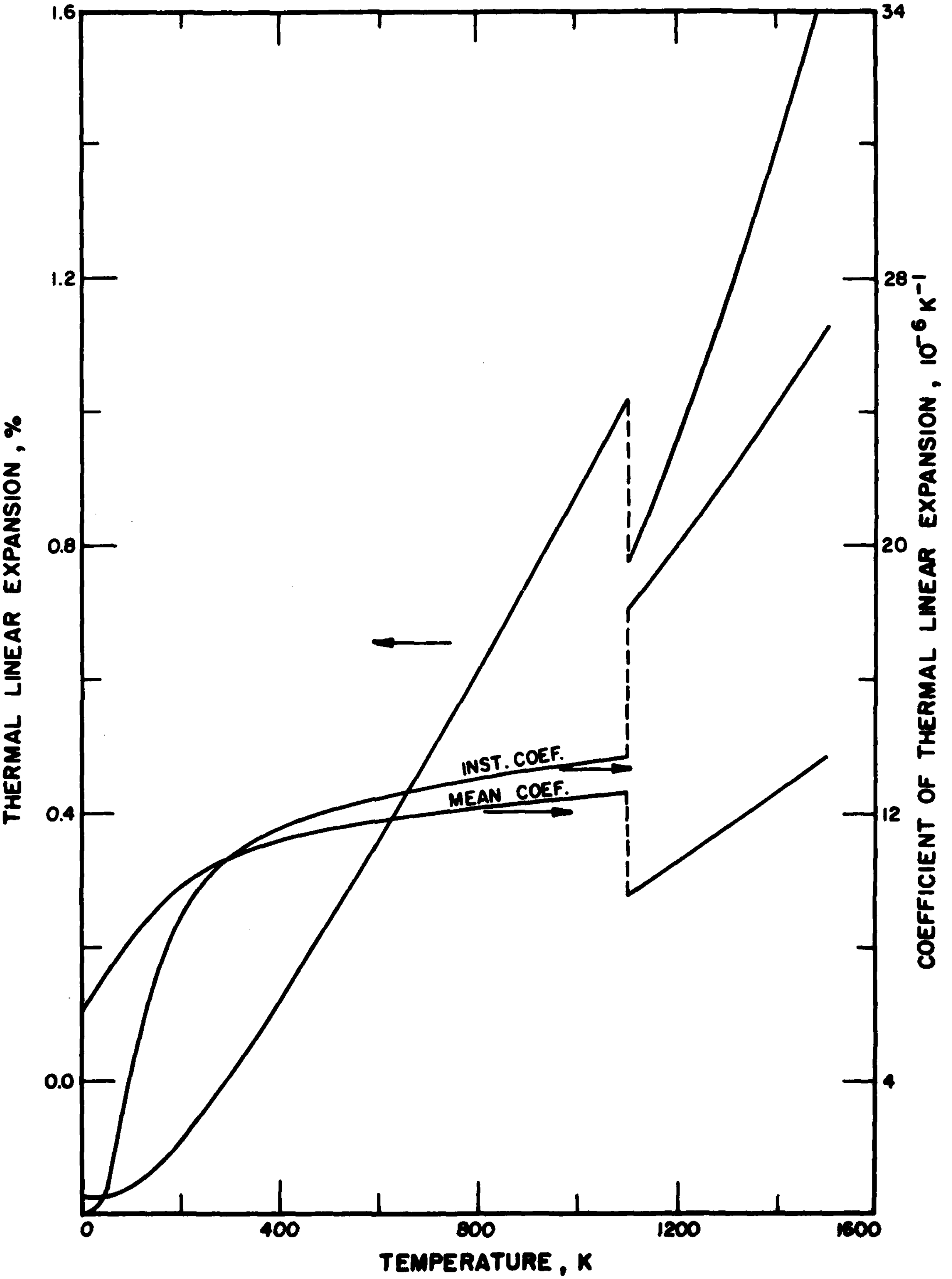

Figure 8. Thermal Linear Expansion of AISI 410 Stainless Steel

9. AISI 430 Stainless Steel

AISI 430 stainless steel is ferritic at all temperatures because of its high (16-18%) chromium content. It is not hardenable by heat treatment, even tought it may develop some austenitic structure upon heating. The amount of austenite is probably insufficient to alter its properties significantly. Similarly, no significant martensite is formed on cooling. This steel is susceptible to embrittlement at 750 K (890°F), and therefore it is usually annealed above this temperature.

There are seven sets of experimental data available for the thermal linear expansion of AISI 430 stainless steel or similar materials [10,27,28,30]. These data sets cover the temperature range 10-1183 K. The recommended values are derived primarily from the data reported by Shulga and Zamora [28] and Clark [30]. An α-γ transformation takes place near 1250 K and this is shown by a sudden drop in the percent thermal linear expansion values. However, no experimental data are available for the thermal linear expansion near and above this transition. Since this steel is austenitic above 1250 K, the values recommended for AISI 410 stainless steel in the austenitic temperature range are adopted for this steel above 1250 K.

The values of the mean coefficient of thermal expansion are calculated from the recommended thermal linear expansion values. The values of the instantaneous coefficient are primarily based on the data reported by Shulga and Zamora [28], using also the values obtained by differentiation of empirical equations used to fit the thermal linear expansion values.

As in the case of AISI 410 stainless steel, there is no metallurgical transformation in this steel upon cold working. The thermal expansion is, therefore, not altered significantly upon cold working.

The recommended values are tabulated in Table 9 and shown in Figure 9. The uncertainty in the recommended values of the percent thermal linear expansion and of the mean coefficient is within ±5% below 1000 K and ±10% above that temperature. The uncertainty in the instantaneous coefficient values is about ±15%.

Table 9. Thermal Linear Expansion of AISI 430 Stainless Steel†

Temperature (K)	Thermal Linear Expansion (%)	Instantaneous Coefficient of Thermal Linear Expansion (10^{-6} K^{-1})	Mean Coefficient of Thermal Linear Expansion¶ (10^{-6} K^{-1})
10	-0.187	0.01	6.61
20	-0.187	0.32	6.85
30	-0.186	1.02	7.07
40	-0.185	1.70	7.31
50	-0.183	2.35	7.53
60	-0.180	2.98	7.73
70	-0.177	3.57	7.94
80	-0.173	4.15	8.12
90	-0.169	4.69	8.33
100	-0.164	5.21	8.50
150	-0.132	7.39	9.23
200	-0.091	8.89	9.78
250	-0.044	9.90	10.15
273	-0.021	10.25	10.38
293	0.000	10.50	---
300	0.007	10.60	10.50
350	0.062	11.18	10.80
400	0.119	11.63	11.12
500	0.239	12.35	11.55
600	0.365	12.90	11.89
700	0.497	13.40	12.21
800	0.633	13.80	12.49
900	0.772	14.10	12.72
1000	0.915	14.37	12.94
1100	1.060	14.60	13.14
1200	1.206*	14.77*	13.30*
1250§	1.282*	14.85*	13.40*
1250§	1.065*	21.01*	11.13*
1300	1.170*	21.99*	11.62*
1350	1.282*	23.19*	12.13*
1400	1.396*	24.30*	12.61*
1450	1.520*	25.42*	13.14*
1500	1.660*	26.55*	13.75*

* Extrapolated values.
† For the uncertainty in the recommended values, see text.
§ α-γ phase transformation.
¶ Mean coefficient from 293 K to indicated temperature.

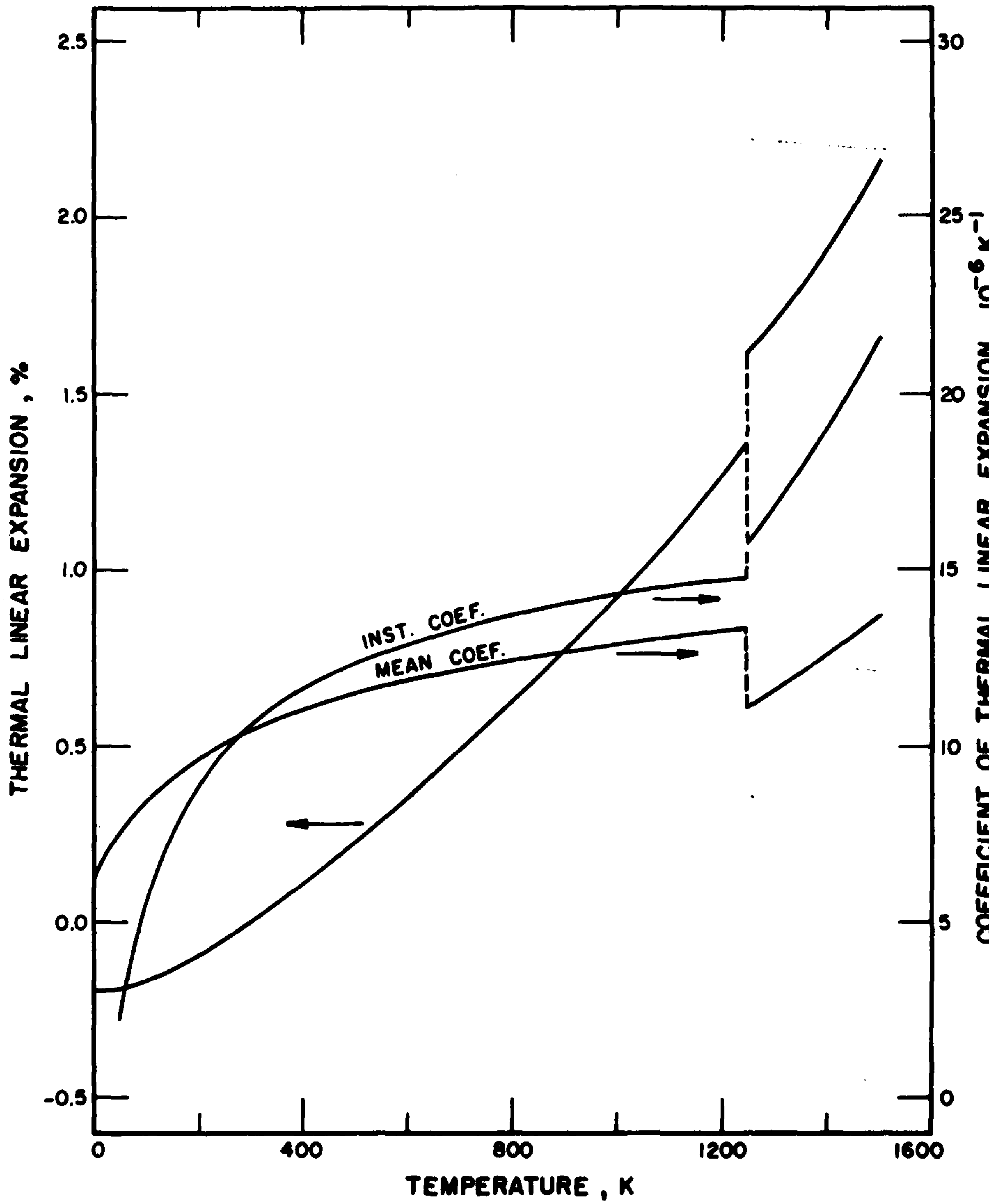

Figure 9. Thermal Linear Expansion of 430 Stainless Steel

V. CONCLUSIONS

The present study of the thermal linear expansion of seven austenitic (AISI 303, 304, 304L, 316, 317, 321, 347) stainless steels indicate that there is consistent similarity in the magnitude and in the temperature dependence of the thermal linear expansion. For example, the thermal linear expansion values of the stainless steels listed above are very close with the exception of AISI 321 stainless steel whose values are about 2-7% lower. For the purpose of comparison, the recommended thermal linear expansion values for AISI 304 and 321 stainless steels are shown together in Figure 10, and the recommended values of the instantaneous coefficient of thermal linear expansion are shown in Figure 11.

The martensitic AISI 410 and the ferritic AISI 430 stainless steels are quite different from the austenitic stainless steels. However, the thermal linear expansion values of these two stainless steels are very close. For comparison, the thermal linear expansion values of AISI 410 stainless steel are also shown in Figure 10 and the values of the coefficient of thermal linear expansion are also shown in Figure 11.

As evidenced by the available experimental data on the thermal linear expansion of nine stainless steels reviewed and discussed in this work, it is clear that for some of the stainless steels, the available data are very scarce and serious gaps exist for the temperature dependence for most of them. The resulting recommended self-consistent values that cover the full temperature range go far beyond the limited experimental data and are, therefore, very useful.

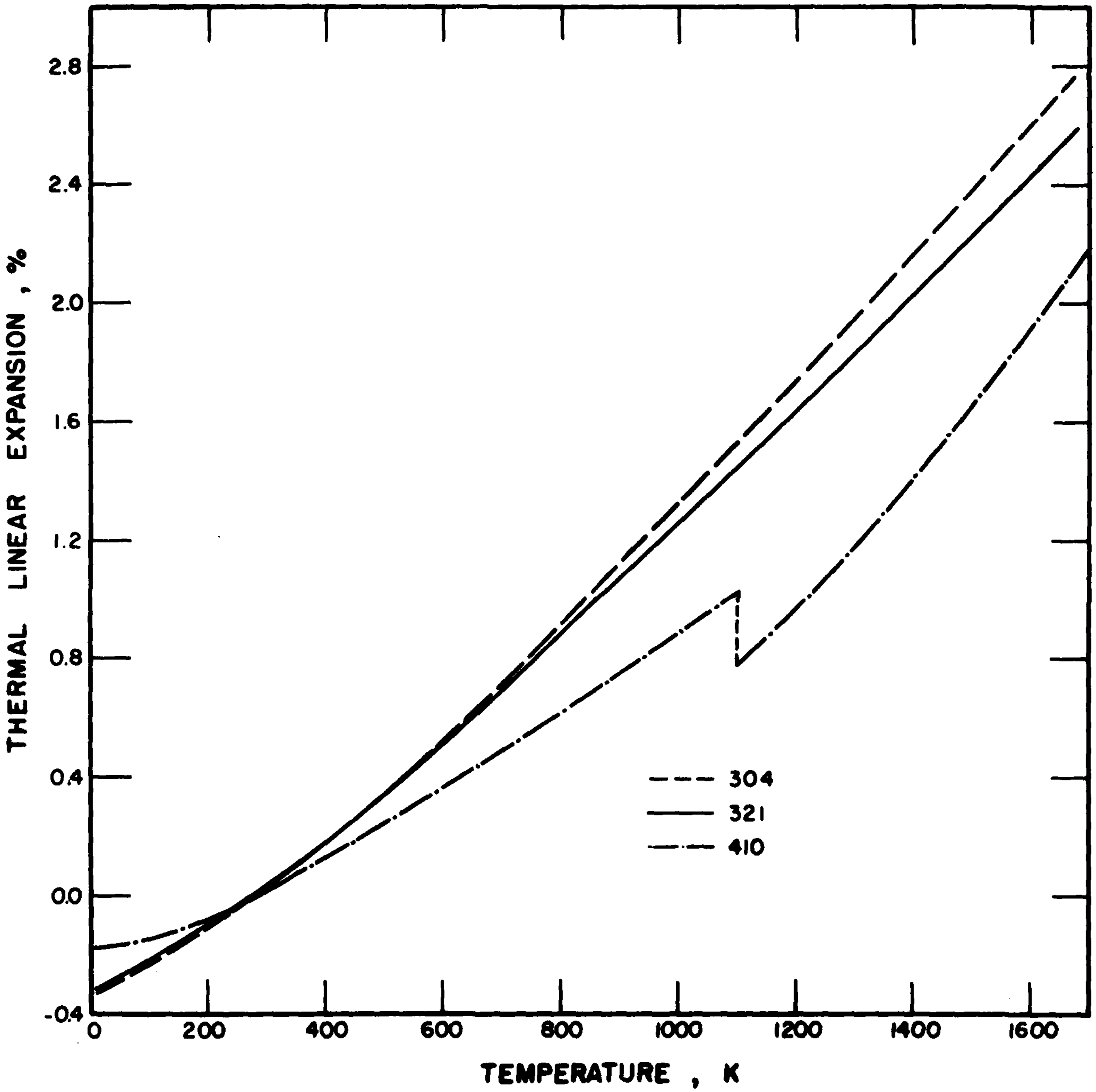

Figure 10. Thermal Linear Expansion of AISI 304, 321 and 410 Stainless Steels

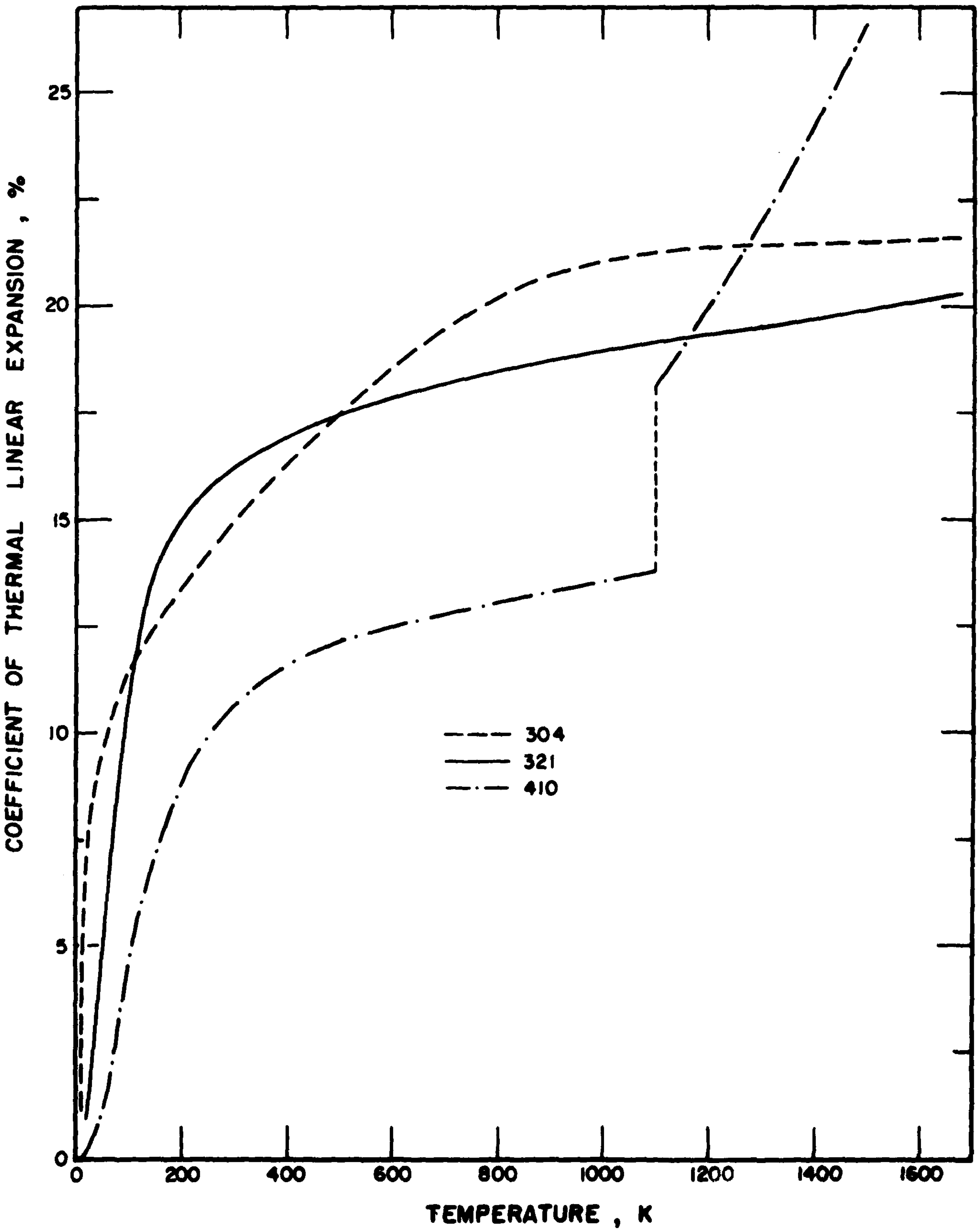

Figure 11. Instantaneous Coefficient of Thermal Linear Expansion of AISI 304, 321 and 410 Stainless Steels.

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