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Argonne National Laboratory

THERMAL EXPANSION OF ALPHA-URANIUM
SINGLE CRYSTALS

by

L. T. Lloyd

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by

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L. T. Lloyd

ABSTRACT

Dilatometric measurements have been obtained between 25° and 650°C from alpha-uranium single crystals in the three principal crystallographic directions. Least mean square fitted equations representing these directions and volume as functions of temperature ($t^{\circ}\text{C}$) are as follows:

$$L_{[100]}_t = L_{[100]}_{0^{\circ}\text{C}} (1 + 23.53 \times 10^{-6}t + 13.74 \times 10^{-9}t^2 + 9.94 \times 10^{-12}t^3)$$

$$L_{[010]}_t = L_{[010]}_{0^{\circ}\text{C}} (1 + 1.16 \times 10^{-6}t - 9.43 \times 10^{-9}t^2 - 11.79 \times 10^{-12}t^3)$$

$$L_{[001]}_t = L_{[001]}_{0^{\circ}\text{C}} (1 + 19.38 \times 10^{-6}t + 21.58 \times 10^{-9}t^2 + 3.32 \times 10^{-12}t^3)$$

$$V_t = V_{0^{\circ}\text{C}} (1 + 43.98 \times 10^{-6}t + 26.88 \times 10^{-9}t^2 + 1.00 \times 10^{-12}t^3)$$

Comparisons of fraction expansions of single crystals with those derived from lattice parameter measurements indicate that portions of the latter data are subject to errors because of elastic interactions between grains of polycrystalline samples.

I. INTRODUCTION

To understand some of the phenomena observed in alpha-uranium, it is necessary to know its expansion with temperature. Also, this information is basic to other physical property measurements. Since the lattice structure is orthorhombic, alpha-uranium has different thermal expansions for the three principal crystal axes; consequently, these values can not be measured directly from polycrystalline materials.

Thermal expansions for the principal directions have been derived from lattice parameter measurements of polycrystalline samples at various temperatures as reported by Bridge, Schwartz and Vaughan,⁽¹⁾ Chiotti, Klepfer and White⁽²⁾ and Konobeevsky et al.⁽³⁾ Thermal cycling studies have shown that polycrystalline alpha-uranium⁽⁴⁾ is subject to gross plastic deformations upon heating and cooling as well as to residual elastic strains. Since the lattice parameter studies were performed with polycrystalline samples, elastic strains may have been present and the observed lattice parameters could be in error. Likewise, the derived expansions could be incorrect.

Single crystal expansion measurements obviously are not subject to errors introduced by elastic strains associated with grain interactions, and they should yield true expansion data. Measurements of this type have been reported by Lehr and Langeron^(5,6) for alpha-uranium "single crystals" grown by cooling in a temperature gradient through the β to α transformation.^(7,8,9) Samples prepared in this manner contain lineage structure and are not truly single crystals. Their studies were of randomly oriented "crystals"; consequently, measurements were not made specifically along the principal crystal axes although they did derive mean thermal expansion coefficients for these directions.

A technique has been developed for preparing alpha-uranium single crystals that do not contain lineage structures. These are of sufficient size to permit preparation of two parallel surfaces of specific crystallographic orientation, and their expansion with temperature can be measured by dilatometric techniques. This report describes single crystal dilatation measurements and compares the results to previous data.

II. EXPERIMENTAL PROCEDURES

A. Sample Preparation

Alpha-uranium single crystals were obtained by the grain coarsening technique described by Fisher.⁽¹⁰⁾ Their sizes, as-grown, ranged up to 0.200" in diameter and approximately $1/2$ " in length. They were isolated from other grains and oriented for metallographic polishing according to techniques described by Lloyd and Chiswick.⁽¹¹⁾ Two parallel surfaces perpendicular to the original sample's axis were developed on the randomly oriented crystals; these defined the crystallographic direction whose dilatation was measured. The samples for principal axes expansion measurements were prepared in the form of pseudo-unit cells with six flat surfaces parallel to the principal crystallographic planes.

Polished surfaces were prepared by normal metallographic techniques of grinding on water lubricated, rotating, silicon carbide papers through 600 mesh, polishing on rotating cloth laps with 3 and 1 micron diamond paste abrasive and electropolishing in a solution of 5 parts 85% orthophosphoric acid, 5 parts ethylene glycol and 8 parts ethyl alcohol at a current density of 30 milliamperes per square centimeter for approximately 10 minutes with a stainless steel cathode and a platinum touch wire. Particular care was taken during these operations so as not to plastically deform the body of the crystals and to minimize the distorted material created during metallographic preparation. In all cases, the thin layer of distorted material was removed by the final electropolish. The surfaces were then carefully observed metallographically and notations were made with regard to the quantity and location of twins and, in a few instances, very fine occluded grains. The crystallographic orientations of the crystals were determined by normal Laue back-reflection techniques.⁽¹²⁾

B. Dilatometric Measurements

Single crystal dilatations with temperature were measured with a Recording Quartz Differential Dilatometer.⁽¹³⁾ Each crystal's original length was determined after electropolishing and just prior to testing to the nearest thousandth of a centimeter with a comparator located in a room of known, constant temperature; at least four measurements were made for each crystal and the recorded lengths are the average of these. The individual crystal was placed into the specimen sleeve of the dilatometer's quartz assembly and quartz "shims" were used to make up the total one inch length provided for specimens. The Pt/Pt-10% Rh temperature measuring thermocouple was placed immediately adjacent to one of the crystal's surfaces. Dilatation curves were obtained with the H' scale of the dilatometer between room temperature and 650°C at heating and cooling rates of approximately 4°C/min. Each crystal was tested several times and expansion data were taken from reproducible curves. After testing the very thin corrosion product film was removed from the crystal by electropolishing and the surfaces were again observed metallographically.

C. Data Treatment

Single crystal expansion data were read from the dilatation curves at 25°C intervals over the range from 25° to 650°C. These data were then multiplied by the appropriate factor for the H' scale, corrected for the expansion of the dilatometer's quartz components and normalized to represent fraction expansion based upon 25°C according to the procedure described in a later part of this report.

Average values of expansion for each 25°C interval and each principal direction were determined from the dilatation data of the crystals tested along the principal axes. These data were then submitted to an IBM 704 computer for least square polynomial fitting to equations of the type:

$$Y = k_0X^0 + k_1X^1 + \dots \dots \dots k_pX^p$$

where: Y represents the dimension at temperature X; $k_0, k_1 \dots \dots \dots k_p$ are constants and p is the order of the polynomial. In all cases equations were determined for p equals 1, 2 and 3. The best fit for each set of data was selected as the equation giving the lowest standard deviation (σ) according to the equation:

$$\sigma = \frac{\sum_{i=1}^N |R_i|}{N} \sqrt{\frac{\pi}{2}}$$

where: N is the number of observations and R_i is the difference between the observed and calculated i th datum point. The experimental lattice parameters of Bridge, Schwartz and Vaughan⁽¹⁾ and Chiotti, Klepfer and White⁽²⁾ also were submitted to this type of equation fitting.

The data obtained from the randomly oriented crystals were compared to values for their expansion as calculated from single crystal and lattice parameter expansions in the principal directions according to the relationship:

$$\begin{aligned} \left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right) &= \left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[100]} \cos^2 \alpha \\ &+ \left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[010]} \cos^2 \beta \\ &+ \left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[001]} \cos^2 \gamma \end{aligned}$$

where: $\left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[100]}$ is the fraction expansion in a given crystallographic direction upon going from 25°C to $t^{\circ}\text{C}$, $\left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[100]}$,

$\left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[010]}$ and $\left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right)_{[001]}$ are the fraction expansions

in the indicated principal directions over the same temperature range and α , β and γ are the angles at 25°C between the given direction and the principal directions $[100]$, $[010]$ and $[001]$, respectively. This relationship is the one usually presented in mathematical treatments of thermal expansion (see for example reference 14) for calculating the dilatation with temperature of a random crystallographic direction. Its derivation involves neglecting the second powers of the relatively small fraction expansions and, therefore, it does not yield precise values for randomly oriented alpha-uranium single crystals. The magnitudes of the errors introduced by this simplifying assumption for the randomly oriented crystals considered here, however, are less than the accuracy of the dilatometer used for the measurements.

III. RESULTS

A. Equations Fitted to Lattice Parameter Data

The a_0 , b_0 , c_0 and unit cell volume (V) lattice parameter data of Bridge, Schwartz and Vaughan⁽¹⁾ are plotted in Figures 1, 2, 3 and 4, respectively; both experimental points and fitted curves are shown. The

experimental data are tabulated in Table I together with the difference between the observed and calculated values derived from the following fitted equations:

$$a_{0T} = 2.8353 (1 + 19.50 \times 10^{-6}T - 0.44 \times 10^{-9}T^2 + 15.06 \times 10^{-12}T^3)$$

$$b_{0T} = 5.8673 (1 - 2.18 \times 10^{-6}T + 12.55 \times 10^{-9}T^2 - 18.15 \times 10^{-12}T^3)$$

$$c_{0T} = 4.9276 (1 + 21.75 \times 10^{-6}T - 13.90 \times 10^{-9}T^2 + 23.72 \times 10^{-12}T^3)$$

$$V_T = 81.975 (1 + 36.32 \times 10^{-6}T + 6.95 \times 10^{-9}T^2 + 14.74 \times 10^{-12}T^3)$$

where: a_0 , b_0 , c_0 and V are the lattice dimensions and T is expressed in $^{\circ}\text{K}$. The anomalous datum point at 20°K for the a_0 was considered as a normal point in deriving the a_0 and V equations.

By a simple reference temperature transformation to $^{\circ}\text{C}$ (t) the equations become:

$$a_{0t} = 2.8512 (1 + 22.50 \times 10^{-6}t + 11.83 \times 10^{-9}t^2 + 14.98 \times 10^{-12}t^3)$$

$$b_{0t} = 5.8671 (1 + 0.61 \times 10^{-6}t - 2.32 \times 10^{-9}t^2 - 18.15 \times 10^{-12}t^3)$$

$$c_{0t} = 4.9542 (1 + 19.36 \times 10^{-6}t + 5.50 \times 10^{-9}t^2 + 23.60 \times 10^{-12}t^3)$$

$$V_t = 82.855 (1 + 42.95 \times 10^{-6}t + 18.82 \times 10^{-9}t^2 + 14.59 \times 10^{-12}t^3)$$

Both sets of equations can be converted to express lengths in the principal directions and volume as functions of temperature and the respective values at the zero temperature by substituting $L[100]$, $L[010]$ and $L[001]$ for a_0 , b_0 and c_0 plus the respective lengths and volumes at zero temperature for the appropriate a_0 , b_0 , c_0 and V values. For example, the a_0 equation for $^{\circ}\text{K}$ becomes:

$$L[100]_T = L[100]_{0^{\circ}\text{K}} (1 + 19.50 \times 10^{-6}T - 0.44 \times 10^{-9}T^2 + 15.06 \times 10^{-12}T^3)$$

for length in the $[100]$ direction.

Figures 1, 2, 3 and 4 also plot the lattice parameter data of Chiotti, Klepfer and White⁽²⁾ together with the fitted curves. Table II records their experimental data and the differences between these and values calculated from the following fitted equations:

$$a_{0t} = 2.8522 (1 + 18.51 \times 10^{-6}t + 25.62 \times 10^{-9}t^2)$$

$$b_{0t} = 5.8648 (1 - 0.66 \times 10^{-6}t + 7.59 \times 10^{-9}t^2 - 30.07 \times 10^{-12}t^3)$$

$$c_{0t} = 4.9522 (1 + 15.11 \times 10^{-6}t + 23.70 \times 10^{-9}t^2)$$

$$V_t = 82.838 (1 + 32.62 \times 10^{-6}t + 58.85 \times 10^{-9}t^2 - 31.52 \times 10^{-12}t^3)$$

Finally, Figures 1, 2 and 3 include the curves of lattice parameter as a function of temperature between 0° - 500°C represented by the equations:

$$a_{0t} = 2.852_2 (1 + 21.7 \times 10^{-6}t + 22 \times 10^{-9}t^2)$$

$$b_{0t} = 5.865_0 (1 + 8.5 \times 10^{-6}t - 28 \times 10^{-9}t^2)$$

$$c_{0t} = 4.953_6 (1 + 16.7 \times 10^{-6}t + 21 \times 10^{-9}t^2)$$

reported by Konobeevsky et al.(3) The volume curve calculated from the derived lattice parameters as a function of temperature is shown in Figure 4.

B. Thermal Expansion of Single Crystals

The thermal expansions of 12 alpha-uranium single crystals were determined during the course of the present work. Six of these were used for measurements along the principal axes and the remainder were tested in random directions. With one exception, metallographic observations indicated that only slight changes occurred during heating and cooling. In the case of specimen T_E, measured in the [100] direction, recrystallized grains were found after dilatation testing; therefore, its data have been neglected. In the other crystals a few twins were present prior to the measurements, but the majority of these were absorbed during the first tests and subsequent expansion curves for each crystal were reproducible and essentially unaffected by the remaining small fraction of twinned material. The origin of the twins can be ascribed to stresses associated with other grains affixed to the crystal during cooling from the grain coarsening treatment of the single crystal growth technique. All of the crystals had a thin corrosion product film subsequent to the dilatation testing; however, its thickness was not sufficient to significantly change the crystal's length and it was easily removed by short time electropolishing.

1. Thermal expansion of crystals in the principal directions:

Seven dilatation measurements in directions within 0.5° of the principal crystallographic axes were obtained from 5 pseudo-unit cell single crystals; two crystals were measured in two different principal directions. Two determinations were made of expansion in the [100], three in the [010] and two in the [001].

Table III illustrates the method of treating the data read from experimental expansion curves by converting it to measured expansion of the specimen, correcting for the expansion of quartz components in the dilatometer and normalizing to represent fraction expansion between 25°C

and $t^{\circ}\text{C}$. The indicated dilatation of the crystal (ΔL_E) was read from the Y coordinate of the experimental curve at intervals of 25°C in terms of $1/3''$ to the nearest 0.05 portion thereof. These figures were multiplied by the magnification factor of the dilatometer scale (H' scale, $1/3'' = 1.303 \times 10^{-4}$ inch dilatation) and added to the sample's original length at the reference temperature to yield the indicated length (L_E) of the crystal at $t^{\circ}\text{C}$. The data were then multiplied by the correction factor (K_t) representing the length of a piece of fused quartz at the respective temperature whose length at the reference temperature was exactly one inch. This correction has been discussed in greater detail by Lloyd.⁽¹³⁾ The quartz length values as a function of temperature were determined from the data reported by Souder and Hidnert.⁽¹⁵⁾ The crystal length values (L_t) were then converted to fraction expansion by the relationship

$$\left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}} \right).$$

Treating the data in this manner refers it to a constant reference temperature of 25°C and permits comparison with other data normalized in the same way. Subsequent use of the term expansion will in fact refer to fraction expansion.

The data for the three principal crystallographic directions as determined from the experimental curves in the above manner are given in Tables IV, V and VI. The tables also include expansions derived from the lattice parameter measurements of Bridge et al.⁽¹⁾ and Chiotti et al.⁽²⁾ Finally, the tables give the averages for the single crystal expansion measurements and the differences between these and those calculated from the following least mean square fitted equations:

$$L[100]_t = L[100]_{0^{\circ}\text{C}} (1 + 23.53 \times 10^{-6}t + 13.74 \times 10^{-9}t^2 + 9.94 \times 10^{-12}t^3)$$

$$L[010]_t = L[010]_{0^{\circ}\text{C}} (1 + 1.16 \times 10^{-6}t - 9.43 \times 10^{-9}t^2 - 11.79 \times 10^{-12}t^3)$$

$$L[001]_t = L[001]_{0^{\circ}\text{C}} (1 + 19.38 \times 10^{-6}t + 21.58 \times 10^{-9}t^2 + 3.32 \times 10^{-12}t^3)$$

Figures 5, 6 and 7 compare the thermal expansions of the principal crystallographic directions. Each figure contains curves derived from the lattice parameter data of Bridge et al. and Chiotti et al. plus the curve for the average of the single crystal experimental data. The single crystal results agree well with the curves from lattice parameter data for the [100] direction expansion, whereas the single crystal [010] curve falls below the lattice parameter curves and the [001] falls above.

Table VII gives volume expansion data similar to that for the principal directions. The single crystal values were obtained by taking the product of the three principal direction lengths, based upon a one inch

length at 25°C, at the respective temperatures and converting these to represent fraction volume expansion by the relationship: $\left(\frac{V_t^{\circ\text{C}} - V_{25^{\circ\text{C}}}}{V_{25^{\circ\text{C}}}} \right)$.

The equation fitted to these data by least mean square analysis is:

$$V_t = V_{0^{\circ\text{C}}} (1 + 43.98 \times 10^{-6}t + 26.88 \times 10^{-9}t^2 + 1.00 \times 10^{-12}t^3) .$$

Figure 8 gives the curve for the single crystal volume expansion equation and compares it to similar curves from the data of Bridge et al. and Chiotti et al.; in this case the data agree reasonably well.

2. Thermal expansion of randomly oriented crystals: The testing directions for the six randomly oriented crystals, as determined by Laue back-reflection photograms, are tabulated in Table VIII together with their initial lengths measured at the indicated temperatures. The angular values are accurate within 0.5 degrees. Tables IX, X, XI, XII, XIII and XIV record the experimental expansions after applying the necessary magnification factor and quartz correction and converting them to represent fraction expansions. As was indicated above, if a crystal's orientation is known its expansion can be calculated by a squared direction cosine relationship of the principal direction expansions. Each table contains values determined in this manner using principal direction expansions derived from least mean square fitted equations of the lattice parameter data of Bridge et al. and Chiotti et al. and dilatation measurements of single crystals. Figures 9, 10, 11, 12, 13 and 14 are the plots of measured and calculated expansions for the randomly oriented crystals. The curves calculated from the principal direction expansions derived from the data of Chiotti et al. have not been included in the figures since the values given in the tables show that they would lie above the curves calculated from the data of Bridge et al.

The experimental curves for two of the crystals, 219-2 and 235-B, agree quite well with the expansions calculated from single crystal principal direction data. Two others, 240C and T_G, agree better with the single crystal calculated curves than they do with the curves calculated from the data of Bridge et al. The remaining two crystals, 240A and 240B, show poor agreement with single crystal calculated curves, particularly, 240A which even lies above the lattice parameter data curve.

The deviations of the experimental curves from those calculated using the single crystal principal direction expansions suggest that the particular randomly oriented crystal may contain significant quantities of differently oriented material. It may be noted that the two crystals which showed poor agreement and one of those showing fair agreement are from the same source metal (240). All three of these crystals contain appreciable twins prior to testing whereas the other three did not. Some of the twins in

the 240 crystals persisted after testing and their presence could well explain the poorer agreement with the curves calculated from single crystal principal direction expansions. In any event, it is significant to note that five of the six experimental curves fall below those calculated from the data of Bridge *et al.*

C. Mean Thermal Expansion Coefficients

Another method of reporting thermal expansion is to give the mean coefficients between a reference temperature and $t^{\circ}\text{C}$. Tables XV, XVI, XVII and XVIII record these values for the principal direction and volume thermal expansions of alpha-uranium. The 20°C reference temperature was chosen to permit direct comparison of the values with data reported by Lehr and Langeron.^(5,6) Each table contains mean thermal expansion coefficients calculated from the equations obtained by least mean square fitting of the lattice parameter data reported by Bridge *et al.*⁽¹⁾ and Chiotti *et al.*⁽²⁾ and of single crystal measurements plus the previously reported coefficients.

IV. DISCUSSION

A. Comparison of Fraction Expansion Data

Figures 1, 2, 3 and 4 show the fair agreement between the lattice parameters reported by Bridge *et al.*⁽¹⁾ and Chiotti *et al.*⁽²⁾ however, the values calculated from the equations reported by Konobeevsky *et al.*⁽³⁾ do not agree as well. Undoubtedly, the works of the first two groups of investigators are more nearly correct than that of the last group.

The thermal expansions obtained from dilatometric measurements of single crystals are somewhat different than those derived from the lattice parameter data, namely with regard to the expansion found for the [010] and [001] directions (Figures 6 and 7). It is believed that these differences are caused by elastic strains in the polycrystalline samples employed for the lattice parameter measurements. In effect, these strains prevented the [010] direction from contracting as much as it should and, in opposition, they prevented the [001] direction from expanding.

Three aspects of the data presented herein support this viewpoint. The first is the fair agreement found for the volumetric expansions as derived from the three groups of data (Figure 8). If the restraints associated with the lattice parameter data were not elastic, there could be appreciable differences between the lattice parameter volumetric expansions and the single crystal expansion. This volumetric expansion agreement substantiates the internal validity of each data group. Secondly, the

association of elastic restraints with grain interactions is supported by a comparison of the single crystal expansions with those derived from the two sets of lattice parameter data. In both instances the restraining effect associated with the lattice parameter data of Chiotti *et al.*⁽²⁾ is greater than that indicated from the data of Bridge *et al.*⁽¹⁾ (Figures 6 and 7). This is what might be expected since Chiotti *et al.* used massive samples for their measurements and Bridge *et al.* used more finely divided material in the form of filings; undoubtedly, the elastic restraints in a massive polycrystalline sample would be greater than those in polycrystalline filings. Finally, the over-all better agreement between observed and calculated expansions of randomly oriented crystals (Figures 9, 10, 11, 12, 13 and 14) as determined from the single crystal principal direction expansions indicates that these data are more valid than the lattice parameter data.

B. Comparison of Mean Expansion Coefficients

The mean thermal expansion coefficients given in Tables XV, XVI, XVII and XVIII, of course, bear out the above observations with regard to comparisons of lattice parameter expansions with those of single crystals. The somewhat superior quality of the data of Bridge *et al.* over that of Chiotti *et al.* is substantiated by the better agreement found for the former when compared to the single crystal mean expansion coefficients for volume and the [100] direction. The mean thermal expansion coefficients previously reported by Lehr and Langeron^(5,6) do not show consistent variations with regard to the single crystal data.

C. Lattice Parameter Corrections Derived from Single Crystal Expansion Data

Unfortunately the single crystal expansion data cannot be used to precisely correct the previously reported lattice parameters. Since expansion is a relative measure, the true lattice parameters at some temperature would have to be known before such corrections could be applied. There is no means of determining the temperature where the elastic restraints associated with the previously reported lattice parameter data are zero or at least a minimum; however, intuitively they should be a minimum at high alpha temperatures. If it is assumed that the lattice parameters at 650°C, as determined from the data of Bridge *et al.*, are not subject to elastic restraints, then the corrected lattice parameters shown in Table XIX can be calculated from the single crystal expansion data. Comparison of the calculated values with those derived from least mean square fitted equations for the data of Bridge *et al.* again shows good agreement between a_0 and unit cell volume values, whereas b_0 and c_0 differ significantly. The b_0 lattice parameter calculated from the single crystal expansion is 0.0047 Å greater than the value derived from the lattice parameter data and c_0 is 0.0059 Å smaller. These differences

are considerably greater than the indicated $\pm 0.0005 \text{ \AA}$ accuracy for the lattice parameter measurements and they are greater than the standard deviation for the fitted equations. In view of the present results, it appears that accurate lattice parameters of alpha-uranium cannot be obtained from polycrystalline samples, and only single crystals, not subject to internal elastic strains, can be used to obtain such data.

V. CONCLUSIONS

Thermal expansion measurements performed on alpha-uranium single crystals of known orientation indicate that previously reported lattice parameters obtained from polycrystalline samples are subject to errors because of elastic interactions between grains. Contraction in the [010] direction is restrained by the interactions as is expansion in the [001] direction. Single crystal and lattice parameter data for volumetric expansion and expansion in the [100] direction agree well. Equations representing expansion in the three principal directions and volumetric expansion as derived from single crystal dilatation measurements are given in the report.

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TABLE I

Alpha-Uranium Lattice Parameter Data of Bridge, Schwartz and Vaughan⁽¹⁾

Temperature (°K)	a_0 - (Å)		b_0 - (Å)		c_0 - (Å)		Unit Cell Volume - (Å ³)	
	Observed	R ₁ *	Observed	R ₁	Observed	R ₁	$a_0 b_0 c_0$	R ₁
20	2 8416	-0 00518	5 8657	0 0013 ₄	4 9306	-0 0008 ₄	82 183	-0 147 ₉
63	2 8363	0 0025 ₀	5 8662	0 0005 ₂	4 9358	-0 0016 ₅	82 123	0 042 ₄
63	2 8394	-0 0006 ₀	5 8666	0 0001 ₂	4 9316	0 0025 ₅	82 149	0 016 ₄
88	2 8378	0 0023 ₉	5 8664	0 0002 ₃	4 9352	0 0014 ₂	82 160	0 082 ₆
88	2 8413	-0 0011 ₁	5 8679	-0 0012 ₇	4 9389	-0 0022 ₈	82 344	-0 101 ₄
123	2 8432	-0 0010 ₃	5 8682	-0 0016 ₀	4 9396	0 0004 ₀	82 415	-0 062 ₆
123	2 8388	0 0033 ₇	5 8662	0 0004 ₀	4 9421	-0 0021 ₀	82 301	0 051 ₄
173	2 8420	0 0030 ₆	5 8671	-0 0004 ₀	4 9429	0 0018 ₄	82 194	0 319 ₇
173	2 8434	0 0016 ₆	5 8693	-0 0026 ₀	4 9456	-0 0008 ₆	82 536	-0 022 ₃
188	2 8450	0 0009 ₄	5 8645	0 0022 ₅	4 9426	0 0035 ₅	82 466	0 097 ₂
300	2 8541	-0 0011 ₆	5 8692	-0 0020 ₃	4 9548	0 0019 ₉	82 999	-0 046 ₅
300	2 8551	-0 0021 ₆	5 8682	-0 0010 ₃	4 9570	-0 0002 ₁	83 051	-0 098 ₅
300	2 8531	-0 0001 ₆	5 8656	0 0015 ₇	4 9571	-0 0003 ₁	82 958	-0 005 ₅
370	2 8605	-0 0027 ₄	5 8673	-0 0000 ₉	4 9636	0 0002 ₄	83 306	-0 089 ₈
373	2 8580	-0 0000 ₃	5 8663	0 0009 ₀	4 9621	0 0020 ₆	83 194	0 033 ₉
375	2 8612	-0 0030 ₈	5 8669	0 0003 ₀	4 9672	-0 0028 ₃	83 381	-0 145 ₃
375	2 8592	-0 0011 ₈	5 8659	0 0013 ₀	4 9685	-0 0041 ₃	83 334	-0 098 ₃
448	2 8612	0 0021 ₇	5 8672	-0 0004 ₈	4 9716	0 0008 ₂	83 468	0 064 ₂
473	2 8659	-0 0002 ₀	5 8644	0 0020 ₀	4 9769	-0 0015 ₁	83 646	-0 007 ₀
548	2 8720	0 0002 ₆	5 8637	0 0011 ₃	4 9875	-0 0024 ₅	83 992	-0 015 ₀
598	2 8759	0 0011 ₆	5 8651	-0 0019 ₄	4 9901	0 0021 ₄	84 170	0 048 ₀
673	2 8866	-0 0016 ₃	5 8627	-0 0031 ₈	4 9993	0 0050 ₉	84 604	0 001 ₆
673	2 8821	0 0028 ₇	5 8563	0 0032 ₂	5 0040	0 0003 ₉	84 460	0 145 ₆
724	2 8900	0 0008 ₉	5 8558	0 0003 ₆	5 0146	-0 0008 ₉	84 863	0 025 ₃
748	2 8924	0 0014 ₄	5 8539	0 0004 ₀	5 0176	0 0008 ₂	84 957	0 070 ₁
794	2 9007	-0 0009 ₀	5 8550	-0 0048 ₀	5 0284	-0 0003 ₁	85 400	-0 096 ₄
823	2 9052	-0 0014 ₃	5 8456	0 0016 ₂	5 0396	-0 0049 ₇	85 586	-0 100 ₆
845	2 9055	0 0014 ₀	5 8443	0 0004 ₅	5 0379	0 0019 ₅	85 547	0 080 ₄
885	2 9156	-0 0027 ₄	5 8386	0 0011 ₇	5 0533	-0 0034 ₁	86 022	-0 127 ₆
913	2 9160	0 0012 ₄	5 8358	0 0000 ₉	5 0539	0 0034 ₈	86 003	0 085 ₅
Standard deviation (σ)	0 0021 ₂		0 0016 ₂		0 0024 ₀		0 097 ₃	

*R₁ = Difference between value calculated from least mean square fitted equation and observed value

TABLE II

Alpha-Uranium Lattice Parameter Data of Chiotti, Klepfer and White⁽²⁾

Temperature °C	$a_0 - (\text{Å})$		$b_0 - (\text{Å})$		$c_0 - (\text{Å})$		Unit Cell Volume - (Å^3)	
	Observed	Ri*	Observed	Ri	Observed	Ri	Observed	Ri
20	2.8526	0.0006 ₅	5.8682	-0.0034 ₄	4.9489	0.0048 ₂	82.843	0.051 ₂
20	2.8537	-0.0004 ₅	5.8619	0.0028 ₆	4.9565	-0.0027 ₈	82.912	-0.018 ₈
27	2.8543	-0.0006 ₆	5.8641	0.0006 ₄	4.9575	-0.0032 ₂	82.978	-0.063 ₃
101	2.8578	0.0004 ₄	5.8636	0.0011 ₀	4.9616	-0.0006 ₈	83.142	0.016 ₂
105	2.8582	0.0003 ₁	5.8660	-0.0013 ₀	4.9578	0.0035 ₂	83.123	0.049 ₇
200	2.8662	-0.0005 ₅	5.8649	-0.0004 ₉	4.9705	0.0013 ₃	83.554	-0.001 ₂
204	2.8657	0.0002 ₈	5.8634	0.0009 ₈	4.9741	-0.0017 ₈	83.578	-0.007 ₈
212	2.8663	0.0003 ₄	5.8646	-0.0002 ₈	4.9751	-0.0017 ₉	83.630	-0.024 ₇
304	2.8751	-0.0001 ₃	5.8636	-0.0008 ₀	4.9844	0.0013 ₇	84.029	0.007 ₈
306	2.8756	-0.0004 ₄	5.8620	0.0007 ₅	4.9881	-0.0020 ₄	84.083	-0.036 ₃
400	2.8849	0.0000 ₈	5.8594	-0.0003 ₀	4.9985	0.0023 ₈	84.494	0.038 ₀
400	2.8845	0.0004 ₈	5.8602	-0.0011 ₀	4.9996	0.0012 ₈	84.512	0.020 ₀
403	2.8859	-0.0005 ₉	5.8575	0.0014 ₄	5.0033	-0.0019 ₁	84.576	-0.028 ₀
505	2.8971	0.0003 ₆	5.8516	-0.0001 ₀	5.0203	-0.0004 ₁	85.107	0.002 ₈
602	2.9113	-0.0008 ₅	5.8402	-0.0000 ₆	5.0394	0.0003 ₆	85.683	-0.021 ₀
603	2.9106	-0.0000 ₃	5.8406	-0.0006 ₀	5.0407	-0.0007 ₃	85.690	-0.022 ₂
603	2.9098	0.0007 ₇	5.8393	0.0007 ₀	5.0397	0.0002 ₇	85.630	0.037 ₈
Standard deviation (σ)	0.0005 ₅		0.0012 ₅		0.0022 ₆		0.032 ₉	

*Ri = Difference between value calculated from least mean square fitted equation and observed value.

TABLE III

Thermal Expansion of Crystal T_D in the [100] Direction*

t	ΔL_E	L_E	K_t	L_t	$\frac{L_t - L_{25^\circ C}}{L_{25^\circ C}} \times 10^4$
24	0.00	0.129920	1.000000	0.129920	-
25	0.05	0.129926	1.000001	0.129927	0.00
50	0.50	0.129985	1.000015	0.129987	4.66
75	1.05	0.130057	1.000030	0.130061	10.32
100	1.60	0.130128	1.000044	0.130134	15.98
125	2.25	0.130213	1.000058	0.130221	22.65
150	2.90	0.130298	1.000073	0.130307	29.31
175	3.70	0.130402	1.000087	0.130413	37.47
200	4.40	0.130493	1.000101	0.130506	44.63
225	5.20	0.130598	1.000115	0.130612	52.80
250	5.90	0.130689	1.000129	0.130706	59.96
275	6.60	0.130780	1.000142	0.130798	67.11
300	7.40	0.130884	1.000155	0.130904	75.27
325	8.30	0.131001	1.000169	0.131024	84.43
350	9.20	0.131119	1.000182	0.131143	93.59
375	10.15	0.131242	1.000195	0.131268	103.25
400	11.15	0.131373	1.000208	0.131400	113.41
425	12.15	0.131503	1.000220	0.131532	123.57
450	13.20	0.131640	1.000233	0.131671	134.23
475	14.20	0.131770	1.000245	0.131802	144.38
500	15.35	0.131920	1.000257	0.131954	156.04
525	16.55	0.132076	1.000269	0.132112	168.20
550	17.65	0.132220	1.000281	0.132257	179.36
575	18.75	0.132363	1.000293	0.132402	190.52
600	20.50	0.132591	1.000307	0.132632	208.18
625	21.80	0.132760	1.000316	0.132802	221.35
650	23.20	0.132943	1.000328	0.132986	235.51

*t = temperature - °C.

 ΔL_E = indicated dilatation in units of $1/3''$ as read from dilatometer curve. L_E = indicated length of crystal = measured length of crystal at reference temperature ($24^\circ C$) plus magnification factor for H' scale of dilatometer (1.303×10^{-4}) times ΔL_E .

$$= 0.12992 + 1.303 \times 10^{-4} \cdot \Delta L_E.$$

 K_t = correction factor due to dilatation of quartz components in the dilatometer.= length of a piece of quartz at t whose length at $24^\circ C$ equals 1.000000.

$$L_t = K_t \cdot L_E$$

$$\frac{L_t - L_{25^\circ C}}{L_{25^\circ C}} = \text{fraction expansion between } 25^\circ C \text{ and } t^\circ C.$$

TABLE IV

Alpha-Uranium Thermal Expansion in the [100] Direction - $\left(\frac{L_{t^{\circ}\text{C}} - L_{25^{\circ}\text{C}}}{L_{25^{\circ}\text{C}}}\right)$

Temperature (°C)	Data from Single Crystals x 10 ⁴				Data from Lattice Parameter x 10 ⁴	
	Crystal T _D L _{24°C} = 0 12992"	Crystal T _F L _{24°C} = 0 14665"	Average	R ₁ *	Bridge, Schwartz and Vaughan	Chotti, Klepfer and White
25	0 00	0 00	0 00	-1 34 ₉	0 00	0 00
50	4 66	5 03	4 84	-0 05 ₀	5 86	5 11
75	10 32	10 96	10 64	0 49 ₄	11 89	10 52
100	15 98	17 76	16 87	0 79 ₅	18 12	16 27
125	22 64	24 57	23 60	0 80 ₅	24 56	22 34
150	29 31	31 82	30 56	0 81 ₂	31 20	28 73
175	37 47	39 52	38 50	0 07 ₄	38 08	35 43
200	44 63	47 65	46 14	-0 14 ₇	45 20	42 46
225	52 80	55 79	54 30	-0 62 ₃	52 59	49.81
250	59 96	63 92	61 94	-0 34 ₀	60 24	57 47
275	67 11	72 50	69 80	-0 01 ₃	68 20	65 49
300	75 27	81 08	78 18	0 08 ₈	76 45	73 76
325	84 43	89 65	87 04	-0 02 ₉	85 01	82 39
350	93 59	98 67	96 13	-0 07 ₃	93 91	91 34
375	103 25	108 58	105 92	-0 51 ₀	103 15	100 60
400	113 41	118 04	115 72	-0 66 ₂	112 76	110 19
425	123 57	127 94	125 76	-0 71 ₅	122 72	120 09
450	134 23	136 95	135 59	-0 24 ₃	133 08	130 33
475	144 38	147 74	146 06	-0 06 ₈	143 84	140 87
500	156 04	158 08	157 06	-0 07 ₄	155 01	151 74
525	168 20	167 98	168 09	0 25 ₀	166 12	162 92
550	179 36	178 77	179 06	1 00 ₀	178 66	174 43
575	190 52	189 55	190 04	2 12 ₈	191 16	186 26
600	208 17	200 78	204 48	0 16 ₇	204 12	198.40
625	221 35	213 78	217 56	-0 04 ₃	217 58	210 87
650	235 51	229 45	232 48	-1 67 ₅	230 54	223 66

*R₁ = Difference between value calculated from least mean square fitted equation and average value

Standard deviation $\sigma = 0.638 \times 10^{-4}$

Table V

Alpha-Uranium Thermal Expansion in the [010] Direction - $\left(\frac{L_t^{\circ\text{C}} - L_{25^{\circ\text{C}}}}{L_{25^{\circ\text{C}}}} \right)$

Temperature (°C)	Data from Single Crystals x 10 ⁴					Data from Lattice Parameter x 10 ⁴	
	Crystal T _A L _{23°C} = 0 3059 ₁ "	Crystal T _B L _{24°C} = 0 2417 ₃ "	Crystal T _C L _{24°C} = 0 1456 ₇ "	Average	R ₁ *	Bridge, Schwartz and Vaughan	Chotti, Klepfer and White
25	0 00	0 00	0 00	0 00	0 10 ₉	0 00	0 00
50	-0 06	0 14	0 15	0 08	0 13 ₂	0 09	-0 06
75	0 08	0 15	0 29	0 17	-0 01 ₀	0 12	-0 08
100	0 01	0 30	0 00	0 10	-0 12 ₆	0 07	-0 08
125	-0 48	-0 36	-0 31	-0 38	0 00 ₉	-0 09	-0 11
150	-0 98	-0 49	-1 06	-0 84	-0 05 ₈	-0 35	-0 18
175	-1 48	-0 88	-1 82	-1 39	-0 21 ₉	-0 75	-0 33
200	-2 40	-1 55	-3 02	-2 32	-0 19 ₂	-1 29	-0 58
225	-3 76	-2 36	-4 67	-3 60	-0 03 ₄	-2 00	-0 95
250	-5 11	-3 71	-5 88	-4 90	-0 06 ₁	-2 89	-1 49
275	-6 68	-5 19	-7 53	-6 47	-0 05 ₀	-3 98	-2 22
300	-8 46	-7 21	-10 08	-8 58	0 27 ₂	-5 29	-3 16
325	-10 25	-8 75	-12 18	-10 47	0 10 ₅	-6 83	-4 34
350	-12 46	-10 99	-14 74	-12 73	0 06 ₀	-8 62	-5 80
375	-14 89	-13 29	-17 74	-15 31	0 05 ₃	-10 67	-7 55
400	-17 32	-15 99	-21 19	-18 17	0 04 ₉	-13 01	-9 63
425	-20 38	-19 10	-25 09	-21 52	0 24 ₇	-15 66	-12 07
450	-23 46	-22 34	-29 44	-25 08	0 33 ₆	-18 62	-14 90
475	-26 74	-25 86	-33 34	-28 65	0 12 ₁	-21 91	-18 13
500	-30 03	-29 65	-38 14	-32 61	-0 03 ₂	-25 56	-21 81
525	-33 74	-34 38	-42 05	-36 72	-0 36 ₄	-29 58	-25 95
550	-38 31	-38 84	-47 30	-41 48	-0 40 ₄	-33 98	-30 60
575	-43 30	-44 39	-52 55	-46 75	-0 30 ₁	-38 79	-35 76
600	-49 15	-49 93	-58 25	-52 44	-0 13 ₆	-44 02	-41 48
625	-54 58	-55 75	-65 29	-58 54	0 04 ₃	-49 68	-47 79
650	-60 43	-62 11	-73 23	-65 26	0 44 ₉	-55 80	-54 70

*R₁ = Difference between value calculated from least mean square fitted equation and average value Standard deviation = 0 19₁ x 10⁻⁴

TABLE VI

Alpha-Uranium Thermal Expansion in the [001] Direction - $\left(\frac{L_{t^{\circ}C} - L_{25^{\circ}C}}{L_{25^{\circ}C}} \right)$

Temperature (°C)	Data from Single Crystals x 10 ⁴				Data from Lattice Parameters x 10 ⁴	
	Crystal T _C L _{24°C} = 0 1681 ₁ "	Crystal T _D L _{25°C} = 0 1155 ₅ "	Average	R ₁ *	Bridge, Schwartz and Vaughan	Chotti, Klepfer and White
25	0 00	0 00	0 00	0 31 ₅	0 00	0 00
50	5 96	5 22	5 59	-0 02 ₆	4 97	4 23
75	11 14	10 44	10 79	0 29 ₉	10 04	8 74
100	17 88	15 66	16 77	0 12 ₈	15 26	13 55
125	24 22	22 57	23 40	-0 41 ₁	20 63	18 66
150	30 95	28 92	29 94	-0 57 ₅	26 18	24.07
175	37 68	35 26	36 47	-0 45 ₀	31 93	29 73
200	44 41	42 73	43 57	-0 59 ₇	37 91	35 76
225	50 75	49 64	50 20	0 02 ₈	44 13	42 06
250	58 64	56 54	57 59	0 17 ₈	50 62	48 65
275	66 14	64 01	65 08	0 54 ₀	57 40	55 54
300	73 64	72 60	73 12	0 64 ₄	64 49	62 72
325	81 91	82 32	82 12	0 10 ₅	71 91	70 19
350	89 97	90 91	90 44	0 54 ₅	79 70	77 97
375	94 84	101 19	100 02	0 51 ₉	87 86	86 04
400	108 27	110 91	109 59	-0 13 ₀	96 41	94 40
425	117 70	121 18	119 44	-0 26 ₄	105 40	103 06
450	127 13	130 90	129 02	0 20 ₃	114 82	112 03
475	137 33	141 74	139 54	0 04 ₅	124 72	121 27
500	148 31	152 58	150 44	-0 17 ₀	135 10	130 83
525	159 28	163 42	161 35	-0 05 ₃	146 00	140 67
550	171 81	174 82	173 32	-0 65 ₆	157 42	150 82
575	183 95	185 09	184 52	-0 16 ₃	169.41	161 26
600	196 47	196 49	196 48	-0 08 ₅	181 97	171 99
625	209 38	208 45	208 92	-0 13 ₇	195 12	183 03
650	221 90	219 85	220 88	0 63 ₅	208 91	194 35

*R₁ = Difference between value calculated from least mean square fitted equation and average value
Standard deviation = 0 358 x 10⁻⁴

TABLE VII

Volumetric Thermal Expansion of Alpha-Uranium - $\left(\frac{V_{t^{\circ}C} - V_{25^{\circ}C}}{V_{25^{\circ}C}} \right)$

Temperature (°C)	Calculated Volume Expansion x 10 ⁴			
	From Single Crystal Data		From Lattice Parameter Data	
	Ave [100] x Ave [010] x Ave [001]	R ₁ *	Bridge, Schwartz and Vaughan(1)	Chiotti, Klepfer and White(2)
25	0 00	-0 908	0 00	0 00
50	10 52	0 061	11 09	9 21
75	21 62	0 780	22 44	19 10
100	33 78	0 790	34 08	29 64
125	46 68	0 393	46 00	40 80
150	59 75	0 168	58 23	52 54
175	73 70	-0 607	70 77	64 84
200	87 57	-0 946	83 65	77 67
225	101 13	-0 633	96 86	91 00
250	114 93	-0 223	110 44	104 80
275	128 78	0 485	124 38	118 76
300	143 15	1 020	138 72	133 68
325	159 23	0 194	153 44	148 71
350	174 47	0 547	168 59	164 09
375	191 36	-0 398	184 16	179 79
400	208 01	-0 742	200 17	195 78
425	224 64	-0 730	216 63	212 04
450	240 61	0 306	233 57	228 52
475	258 16	0 098	250 98	245 21
500	276 26	-0 288	268 89	262 08
525	294 21	-0 187	287 30	279 09
550	312 52	-0 082	306 24	296 33
575	329 54	1 668	325 71	313 43
600	350 40	-0 064	345 73	330 70
625	369 96	-0 135	366 31	347 98
650	390 24	-0 568	387 48	365 28

*R₁ - Difference between value calculated from least mean square fitted equation and observed value Standard deviation = 0 628 x 10⁻⁴

TABLE VIII

Testing Directions and Initial Lengths of Randomly Oriented Crystals

Crystal Identification	Location of Testing Direction with Respect to Principal Directions (degrees)			Initial Length	
	[100]	[010]	[001]	Average of 4 Measurements (inches)	Measurement Temperature (°C)
219-2	86	13 5	77	0 1139	21
235-B	87	8 5	81 5	0 0939	21
240-A	86 5	13	77 5	0 1484	21
240-B	88 5	10 5	79 5	0 1415	21
240-C	83	13	79	0 1476	21
T _G	84	11	80 5	0 3749	24

TABLE IX

Thermal Expansion of Crystal 219-2

Temperature (t° C)	Thermal Expansion $\times 10^4 - \left(\frac{L_{t^\circ C} - L_{25^\circ C}}{L_{25^\circ C}} \right)$			
	From Dilatation Curve	Calculated from Principal Direction Expansions		
		Single Crystals	Bridge, Schwartz and Vaughan(1)	Chiotti, Klepfer and White(2)
25	0.00	0.00	0.00	0.00
50	0.72	0.48	0.36	0.18
75	1.44	0.76	0.68	0.42
100	1.58	0.90	0.93	0.69
125	1.73	0.91	1.08	0.95
150	1.30	0.77	1.14	1.19
175	0.87	0.47	1.09	1.37
200	0.43	0.00	0.92	1.47
225	-0.57	-0.65	0.60	1.47
250	-1.58	-1.48	0.12	1.33
275	-2.59	-2.52	-0.53	1.03
300	-4.17	-3.76	-1.37	0.54
325	-5.76	-5.23	-2.40	-0.15
350	-7.34	-6.93	-3.66	-1.09
375	-9.50	-8.86	-5.14	-2.30
400	-11.09	-11.05	-6.87	-3.79
425	-13.82	-13.50	-8.87	-5.61
450	-15.99	-16.22	-11.15	-7.78
475	-19.30	-19.22	-13.70	-10.32
500	-22.61	-22.51	-16.58	-13.26
525	-27.06	-26.10	-19.77	-16.62
550	-31.52	-30.01	-23.29	-20.45
575	-36.56	-34.24	-27.17	-24.74
600	-41.02	-38.80	-31.42	-29.55
625	-46.62	-43.70	-36.04	-34.90
650	-49.94	-48.96	-41.06	-40.80

TABLE X
Thermal Expansion of Crystal 235-B

Temperature (t° C)	Thermal Expansion x 10 ⁴ - $\left(\frac{L_{t^{\circ}C} - L_{25^{\circ}C}}{L_{25^{\circ}C}}\right)$			
	From Dilatation Curve	Calculated from Principal Direction Expansions		
		Single Crystals	Bridge, Schwartz and Vaughan ⁽¹⁾	Chiotti, Klepfer and White ⁽²⁾
25	0.00	0.00	0.00	0.00
50	0.15	0.31	0.20	0.04
75	-0.40	0.39	0.34	0.12
100	-0.53	0.34	0.41	0.22
125	-1.08	0.13	0.37	0.31
150	-1.63	-0.25	0.24	0.36
175	-1.91	-0.79	-0.02	0.34
200	-3.16	-1.52	-0.42	0.23
225	-3.71	-2.45	-0.98	0.00
250	-4.96	-3.58	-1.70	-0.38
275	-6.22	-4.93	-2.62	-0.94
300	-7.47	-6.51	-3.74	-1.70
325	-8.73	-8.33	-5.08	-2.69
350	-10.68	-10.39	-6.66	-3.94
375	-12.63	-12.71	-8.49	-5.47
400	-14.58	-15.31	-10.58	-7.32
425	-17.93	-18.19	-12.98	-9.52
450	-20.58	-21.36	-15.66	-12.09
475	-23.93	-24.82	-18.66	-15.04
500	-27.28	-28.61	-22.00	-18.43
525	-31.32	-32.72	-25.69	-22.26
550	-36.06	-37.16	-29.74	-26.58
575	-42.19	-41.95	-34.18	-31.40
600	-46.93	-47.10	-39.02	-36.76
625	-52.37	-52.61	-44.26	-42.68
650	-59.20	-58.50	-49.95	-49.19

TABLE XI

Thermal Expansion of Crystal 240-A

Temperature (t° C)	Thermal Expansion $\times 10^4 - \left(\frac{L_{t^\circ C} - L_{25^\circ C}}{L_{25^\circ C}} \right)$			
	From Dilatation Curve	Calculated from Principal Direction Expansions		
		Single Crystals	Bridge, Schwartz and Vaughan(1)	Chiotti, Klepfer and White(2)
25	0.00	0.00	0.00	0.00
50	0.59	0.46	0.34	0.16
75	1.17	0.70	0.63	0.37
100	1.76	0.82	0.85	0.62
125	1.90	0.79	0.97	0.85
150	1.82	0.62	1.01	1.06
175	1.74	0.28	0.92	1.21
200	1.44	-0.22	0.72	1.28
225	0.70	-0.91	0.36	1.25
250	-0.04	-1.79	-0.15	1.08
275	-0.78	-2.87	-0.84	0.74
300	-1.96	-4.16	-1.72	0.21
325	-3.15	-5.68	-2.80	-0.52
350	-4.34	-7.43	-4.10	-1.51
375	-5.08	-9.42	-5.63	-2.76
400	-6.71	-11.66	-7.41	-4.31
425	-8.34	-14.17	-9.47	-6.18
450	-9.97	-16.95	-11.80	-8.41
475	-12.05	-20.02	-14.42	-11.01
500	-14.56	-23.38	-17.36	-14.01
525	-17.07	-27.05	-20.62	-17.44
550	-20.03	-31.03	-24.22	-21.34
575	-23.42	-35.33	-28.18	-25.70
600	-27.70	-39.98	-32.51	-30.58
625	-31.98	-44.97	-37.21	-36.01
650	-35.81	-50.31	-42.33	-41.99

TABLE XII
Thermal Expansion of Crystal 240-B

Temperature (t° C)	Thermal Expansion x 10 ⁴ - $\left(\frac{L_{t^{\circ}C} - L_{25^{\circ}C}}{L_{25^{\circ}C}} \right)$			
	From Dilatation Curve	Calculated from Principal Direction Expansions		
		Single Crystals	Bridge, Schwartz and Vaughan ⁽¹⁾	Chotti, Klepfer and White ⁽²⁾
25	0 00	0 00	0 00	0 00
50	1 07	0 37	0 26	0 08
75	2 14	0 52	0 48	0 22
100	2 28	0 53	0 59	0 38
125	2 42	0 40	0 61	0 53
150	1 65	0 11	0 55	0 64
175	1 33	-0 35	0 36	0 69
200	1 00	-0 99	0 04	0 66
225	0 22	-1 82	-0 43	0 51
250	-0 56	-2 85	-1 07	0 21
275	-1 81	-4 09	-1 89	-0 26
300	-3 06	-5 55	-2 92	-0 92
325	-4 30	-7 24	-4 16	-1 81
350	-6 02	-9 18	-5 62	-2 96
375	-8 19	-11 35	-7 37	-4 37
400	-9 90	-13 82	-9 30	-6 10
425	-12 54	-16 55	-11 56	-8 16
450	-15 18	-19 56	-14 10	-10.60
475	-18 28	-22 86	-16 94	-13 40
500	-21 84	-26 47	-20 11	-16 64
525	-25 41	-30 40	-23 63	-20 30
550	-29 43	-34 66	-27 50	-24 45
575	-33 46	-39 25	-31 74	-29 09
600	-38 41	-44 19	-36 37	-34 25
625	-44 28	-49 49	-41 40	-39 98
650	-50 16	-55 16	-46 85	-46 27

TABLE XIII
Thermal Expansion of Crystal 240-C

Temperature (t° C)	Thermal Expansion x 10 ⁴ - $\left(\frac{L_{t^{\circ}C} - L_{25^{\circ}C}}{L_{25^{\circ}C}}\right)$			
	From Dilatation Curve	Calculated from Principal Direction Expansions		
		Single Crystals	Bridge, Schwartz and Vaughan ⁽¹⁾	Chotti, Klepfer and White ⁽²⁾
25	0 00	0 00	0 00	0 00
50	1 03	0 47	0 35	0 17
75	2 06	0 73	0 66	0 40
100	2 65	0 86	0 89	0 66
125	2 79	0 84	1 03	0 91
150	2 49	0 68	1 08	1 13
175	1 75	0 35	1 02	1 30
200	1 00	-0 14	0 83	1 38
225	0 26	-0 82	0 49	1 37
250	-1 37	-1 69	-0 01	1 21
275	-2 12	-2 76	-0 68	0 89
300	-3 75	-4 04	-1 54	0 38
325	-4 94	-5 55	-2 60	-0 34
350	-6 58	-7 29	-3 89	-1 31
375	-8 21	-9 27	-5 40	-2 54
400	-10 29	-11 51	-7 17	-4 07
425	-11 93	-14 00	-9 21	-5 92
450	-14 46	-16 78	-11 52	-8 13
475	-16 98	-19 83	-14 12	-10 70
500	-20 39	-23 18	-17 04	-13 69
525	-23 80	-26 84	-20 30	-17 10
550	-27 66	-30 81	-23 88	-20 97
575	-32 40	-35 10	-27 82	-25 31
600	-36 70	-39 73	-32 14	-30 17
625	-41 00	-44 71	-36 83	-35 58
650	-45 74	-50 04	-41 93	-41 53

TABLE XIV
Thermal Expansions of Crystal T_G

Temperature (t° C)	Thermal Expansion x 10 ⁴ - $\left(\frac{L_{t^{\circ}C} - L_{25^{\circ}C}}{L_{25^{\circ}C}}\right)$			
	From Dilatation Curve	Calculated from Principal Direction Expansions		
		Single Crystals	Bridge, Schwartz and Vaughan ⁽¹⁾	Chiotti, Klepfer and White ⁽²⁾
25	0.00	0.00	0.00	0.00
50	0.15	0.40	0.28	0.11
75	0.29	0.58	0.52	0.28
100	0.26	0.63	0.68	0.47
125	0.24	0.53	0.74	0.65
150	0.03	0.27	0.72	0.80
175	-0.18	-0.15	0.56	0.88
200	-0.73	-0.75	0.28	0.88
225	-1.46	-1.54	-0.15	0.78
250	-2.20	-2.52	-0.74	0.52
275	-3.10	-3.72	-1.52	0.09
300	-4.36	-5.14	-2.50	-0.52
325	-5.79	-6.78	-3.68	-1.36
350	-7.75	-8.66	-5.09	-2.46
375	-9.88	-10.78	-6.74	-3.82
400	-12.01	-13.19	-8.66	-5.49
425	-14.66	-15.86	-10.85	-7.49
450	-17.32	-18.81	-13.33	-9.86
475	-20.50	-22.05	-16.11	-12.60
500	-23.51	-25.59	-19.21	-15.76
525	-27.21	-29.45	-22.66	-19.35
550	-31.44	-33.62	-26.45	-23.42
575	-35.49	-38.14	-30.61	-27.97
600	-39.83	-43.00	-35.16	-33.05
625	-45.00	-48.21	-40.10	-38.68
650	-50.62	-53.79	-45.46	-44.88

TABLE XV

Mean Thermal Expansion Coefficients of Alpha-Uranium in the [100] Direction

$$\left(\alpha_{[100]20^\circ \text{C to } t^\circ \text{C}} = \frac{L_{t^\circ \text{C}} - L_{20^\circ \text{C}}}{L_{20^\circ \text{C}}(t^\circ \text{C} - 20^\circ \text{C})} \right)$$

Temperature (t°C)	Mean Thermal Expansion Coefficient Between 20° and t° x 10 ⁶ - (per°C)			
	Calculated from Least Mean Square Fitted Equations			Reported by Lehr and Langeron ^(5,6)
	Single Crystal Expansion	Bridge, Schwartz and Vaughan ⁽¹⁾	Chotti, Klepfer and White ⁽²⁾	
50	24.5	23.4	20.3	
75	24.9	23.7	20.9	
100	25.3	24.1	21.6	
125	25.7	24.5	22.2	
150	26.1	24.9	22.9	
175	26.5	25.3	23.5	
200	27.0	25.8	24.1	22.4
225	27.4	26.2	24.8	
250	27.9	26.7	25.4	23.1
275	28.4	27.2	26.1	
300	28.9	27.7	26.7	23.8
325	29.4	28.2	27.3	24.2
350	29.9	28.8	28.0	
375	30.4	29.4	28.6	
400	31.0	30.0	29.2	25.5
425	31.5	30.6	29.9	
450	32.1	31.2	30.5	
475	32.6	31.9	31.2	27.1
500	33.2	32.5	31.8	27.7
525	33.8	33.2	32.5	
550	34.5	33.9	33.1	29.0
575	35.1	34.6	33.7	
600	35.7	35.4	34.4	30.5
625	36.4	36.2	35.0	31.3
650	37.0	36.9	35.7	

TABLE XVI

Mean Thermal Expansion Coefficients of Alpha-Uranium in the [010] Direction

$$\left(\alpha_{[010]20^\circ \text{C to } t^\circ \text{C}} = \frac{L_{t^\circ \text{C}} - L_{20^\circ \text{C}}}{L_{20^\circ \text{C}}(t^\circ \text{C} - 20^\circ \text{C})} \right)$$

Temperature (t°C)	Mean Thermal Expansion Coefficient Between 20° and t°C x 10 ⁶ - (per °C)			
	Calculated from Least Mean Square Fitted Equations			Reported by Lehr and Langeron ⁽⁵⁶⁾
	Single Crystal Expansion	Bridge, Schwartz and Vaughan ⁽¹⁾	Chiotti, Klepfer and White ⁽²⁾	
50	0.5	0.4	-0.3	
75	0.2	0.2	-0.2	
100	-0.2	0.1	-0.1	
125	-0.4	-0.1	-0.1	
150	-0.7	-0.2	-0.1	
175	-1.1	-0.5	-0.2	
200	-1.4	-0.7	-0.3	0.2
225	-1.8	-1.0	-0.5	
250	-2.2	-1.2	-0.6	-0.3
275	-2.6	-1.6	-0.9	
300	-2.9	-1.9	-1.1	-1.0
325	-3.4	-2.2	-1.4	-1.3
350	-3.9	-2.6	-1.8	
375	-4.3	-3.0	-2.1	
400	-4.8	-3.4	-2.5	-2.5
425	-5.3	-3.9	-3.0	
450	-5.8	-4.3	-3.5	
475	-6.3	-4.8	-4.0	-3.9
500	-6.8	-5.3	-4.5	-4.4
525	-7.4	-5.8	-5.1	
550	-7.9	-6.4	-5.8	-5.5
575	-8.5	-7.0	-6.4	
600	-9.1	-7.6	-7.2	-6.7
625	-9.7	-8.2	-7.9	-7.5
650	-10.3	-8.8	-8.7	

TABLE XVII

Mean Thermal Expansion Coefficients of Alpha-Uranium in the [001] Direction

$$\left(\alpha_{[001]20^{\circ}\text{C to } t^{\circ}\text{C}} = \frac{L_{t^{\circ}\text{C}} - L_{20^{\circ}\text{C}}}{L_{20^{\circ}\text{C}}(t^{\circ}\text{C} - 20^{\circ}\text{C})} \right)$$

Temperature (t°C)	Mean Thermal Expansion Coefficient Between 20° and t°C x 10 ⁶ - (per °C)			
	Calculated from Least Mean Square Fitted Equations			Reported by Lehr and Langeron ^(5,6)
	Single Crystal Expansion	Bridge, Schwartz and Vaughan ⁽¹⁾	Chiotti, Klepfer and White ⁽²⁾	
50	20.9	19.8	16.8	
75	21.4	20.0	17.3	
100	22.0	20.3	17.9	
125	22.6	20.6	18.5	
150	23.1	20.9	19.1	
175	23.7	21.2	19.7	
200	24.3	21.5	20.3	21.5
225	24.8	22.0	20.9	
250	25.4	22.4	21.5	22.6
275	26.0	22.9	22.1	
300	26.6	23.4	22.7	23.7
325	27.2	23.9	23.3	24.3
350	27.8	24.4	23.9	
375	28.4	25.0	24.5	
400	28.9	25.6	25.0	26.2
425	29.6	26.3	25.6	
450	30.2	26.9	26.2	
475	30.8	27.6	26.8	28.2
500	31.4	28.4	27.4	28.9
525	32.1	29.1	28.0	
550	32.7	29.9	28.6	30.4
575	33.3	30.7	29.2	
600	34.0	31.5	29.8	32.2
625	34.6	32.4	30.4	33.3
650	35.3	33.3	31.0	

TABLE XVIII

Volumetric Mean Thermal Expansion Coefficients of Alpha Uranium

$$\left(\alpha_{V20^\circ \text{ to } t^\circ\text{C}} = \frac{V_{t^\circ\text{C}} - V_{20^\circ\text{C}}}{V_{20^\circ\text{C}}(t^\circ\text{C} - 20^\circ\text{C})} \right)$$

Temperature (t°C)	Volumetric Mean Thermal Expansion Coefficient Between 20°C and t°C x 10 ⁶ - (per °C)			
	Calculated from Least Mean Square Fitted Equations			Reported by Lehr and Langeron*(5,6)
	Single Crystal Expansion	Bridge, Schwartz and Vaughan ⁽¹⁾	Chiotti, Klepfer and White ⁽²⁾	
50	45.8	44.3	36.6	
75	46.5	44.8	37.9	
100	47.2	45.3	39.3	
125	47.9	45.9	40.5	
150	48.5	46.5	41.8	
175	49.2	47.1	43.0	
200	49.9	47.7	44.1	44.4
225	50.6	48.3	45.2	
250	51.2	49.0	46.3	45.5
275	51.9	49.6	47.3	
300	52.6	50.3	48.4	46.8
325	53.3	51.0	49.3	47.2
350	54.0	51.8	50.3	
375	54.7	52.5	51.1	
400	55.4	53.3	51.9	48.9
425	56.1	54.0	52.8	
450	56.8	54.8	53.6	
475	57.5	55.6	54.3	50.8
500	58.2	56.5	55.0	51.6
525	58.9	57.3	55.6	
550	59.6	58.2	56.2	53.1
575	60.3	59.1	56.8	
600	61.0	60.0	57.3	54.9
625	61.7	60.9	57.8	55.8
650	62.4	61.9	58.3	

*Volumetric mean thermal expansion coefficients reported are three times the linear mean thermal expansion coefficient of randomly oriented polycrystalline material

TABLE XIX
Corrected Alpha-Uranium Lattice
Parameters at 25°C

Lattice Parameter	Source	
	Bridge, Schwartz and Vaughan*	Single Crystal Expansion**
$a_0 - (\text{Å})$	2 8528	2 8527
$b_0 - (\text{Å})$	5 8672	5 8725
$c_0 - (\text{Å})$	4 9566	4 9507
$V - (\text{Å}^3)$	82 945	82 920

*Lattice parameters at 25°C calculated from least mean square equations fitted to data of Bridge, Schwartz and Vaughan (1)

**Lattice parameters at 25°C calculated from least mean square equations fitted to single crystal expansion data and assuming the respective lattice parameters at 650°C as given by equations fitted to data of Bridge et al are correct

Figure 1

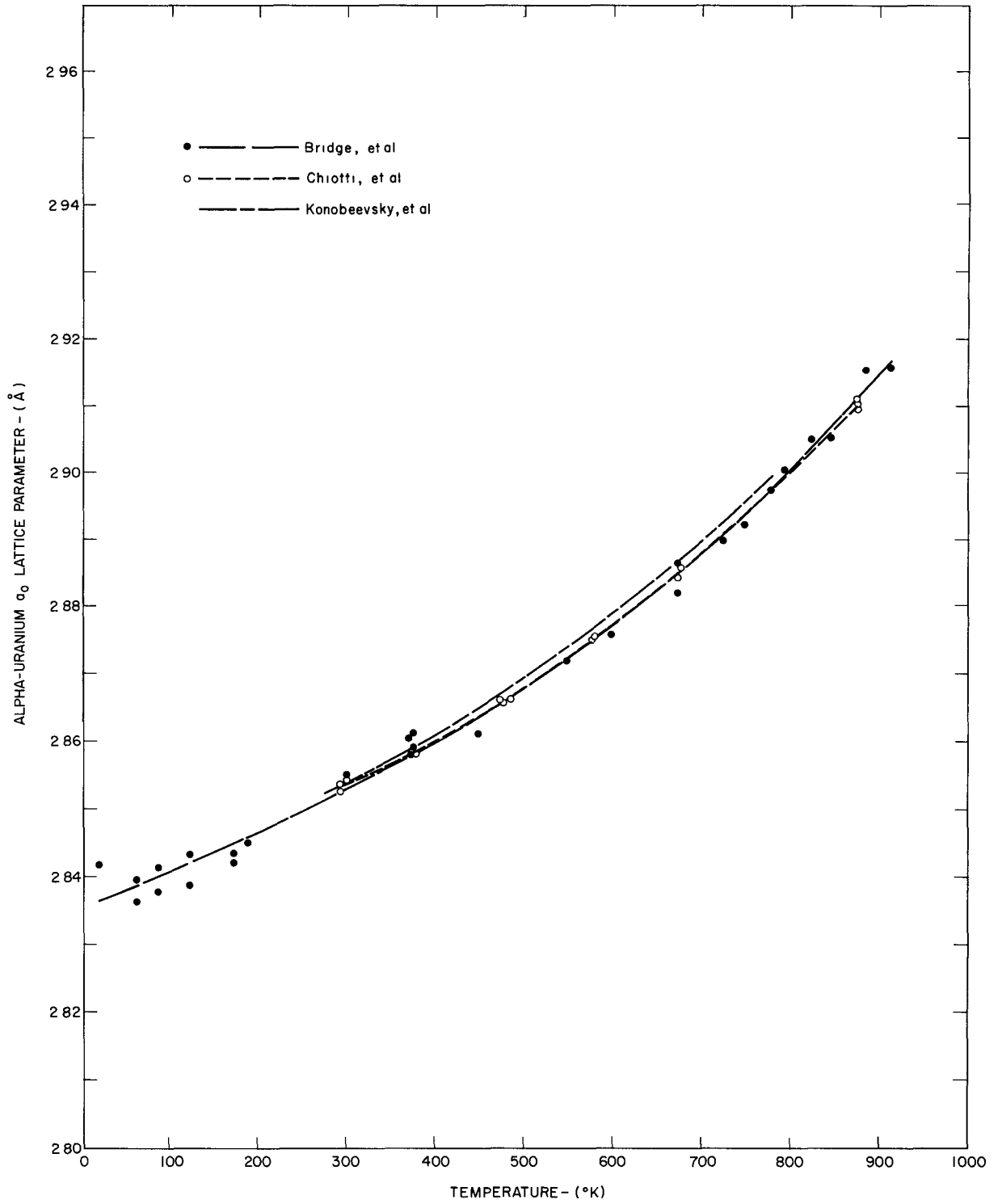
ALPHA-URANIUM a_0 LATTICE PARAMETER VARIATION WITH TEMPERATURE

Figure 2

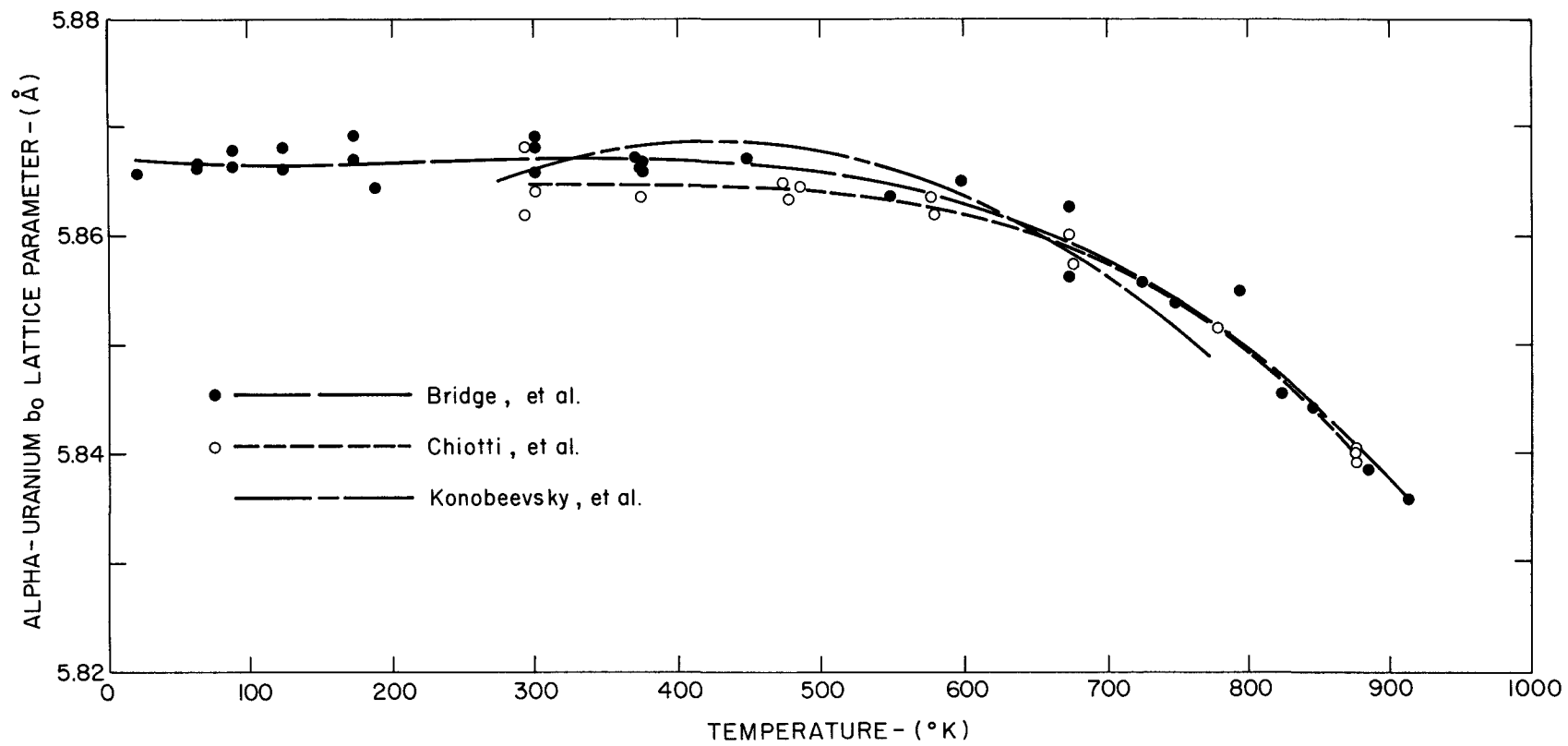
ALPHA-URANIUM b_0 LATTICE PARAMETER VARIATION WITH TEMPERATURE

Figure 3
ALPHA-URANIUM c_0 LATTICE PARAMETER VARIATION WITH TEMPERATURE

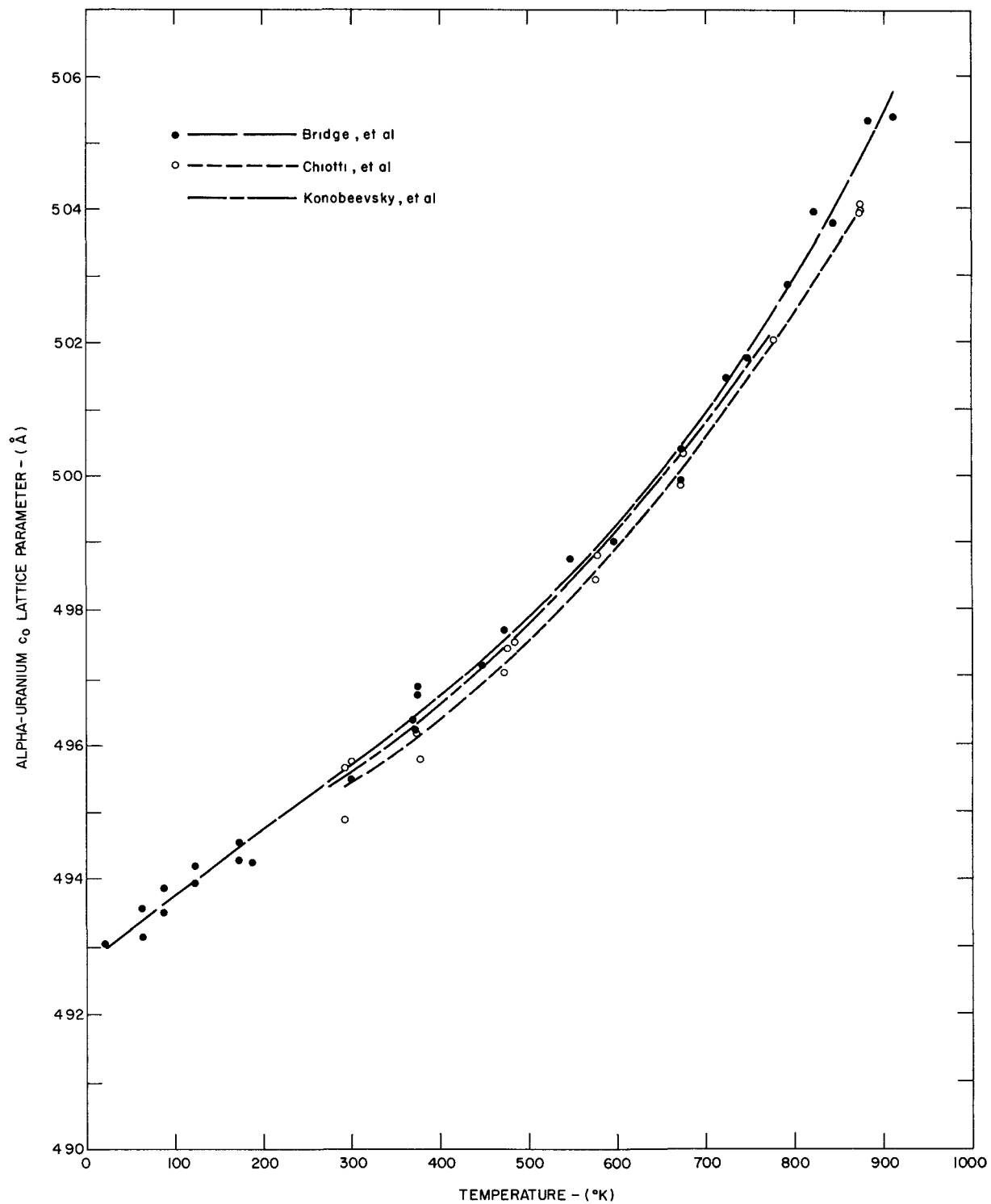


Figure 4
ALPHA-URANIUM UNIT CELL VOLUME VARIATION WITH TEMPERATURE

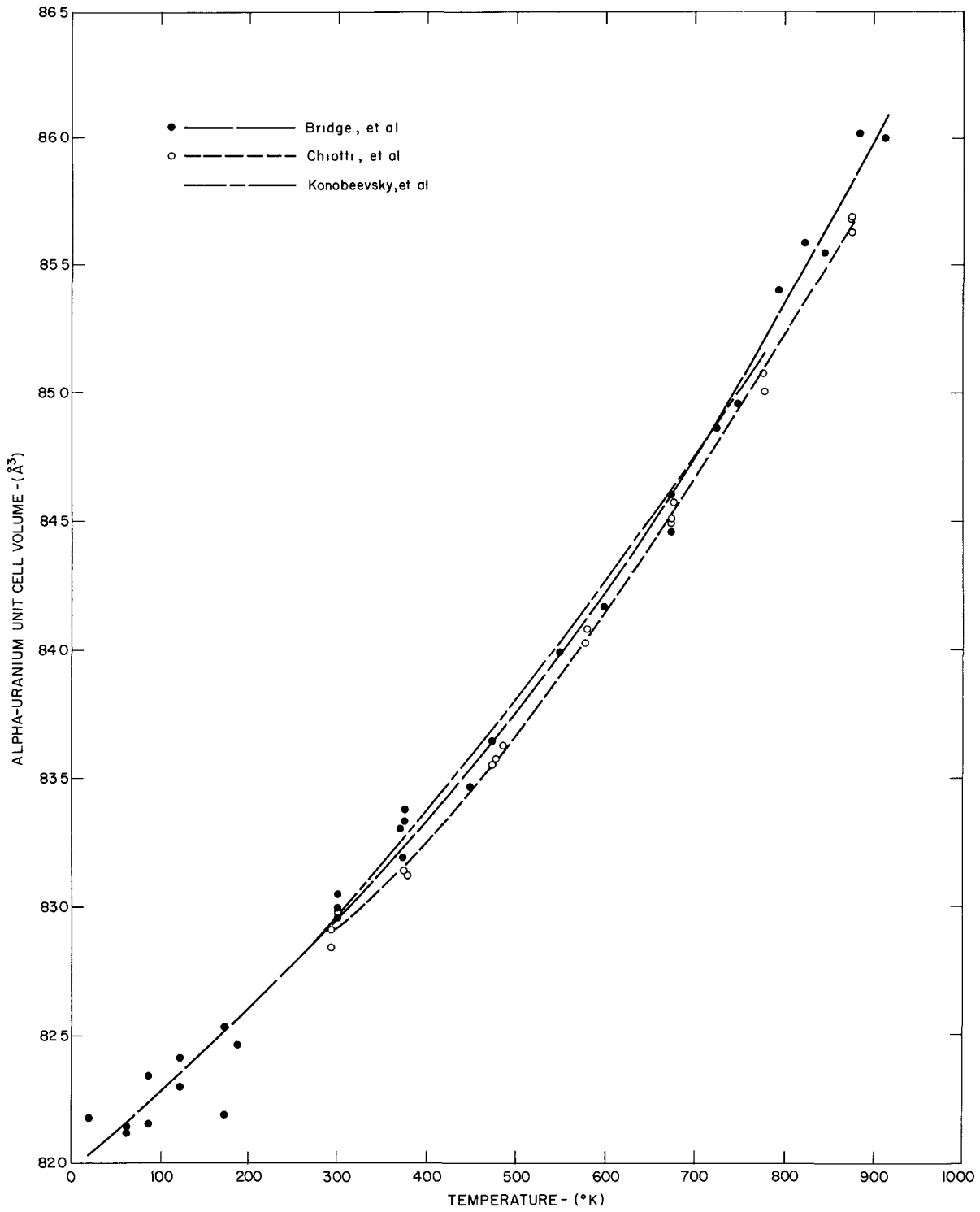


Figure 5

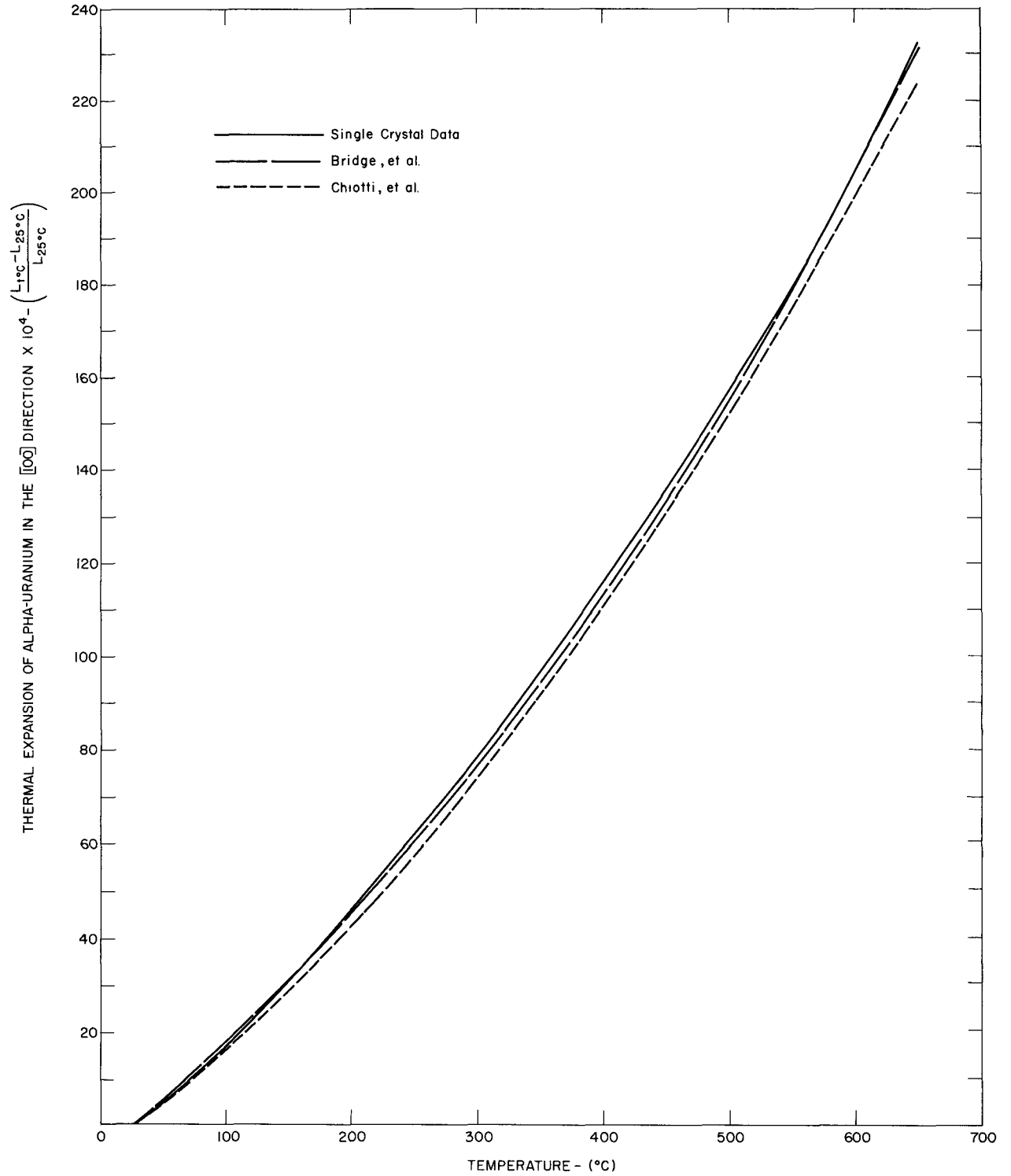
THERMAL EXPANSION OF ALPHA-URANIUM IN THE $[100]$ DIRECTION

Figure 6
THERMAL EXPANSION OF ALPHA-URANIUM IN THE [010] DIRECTION

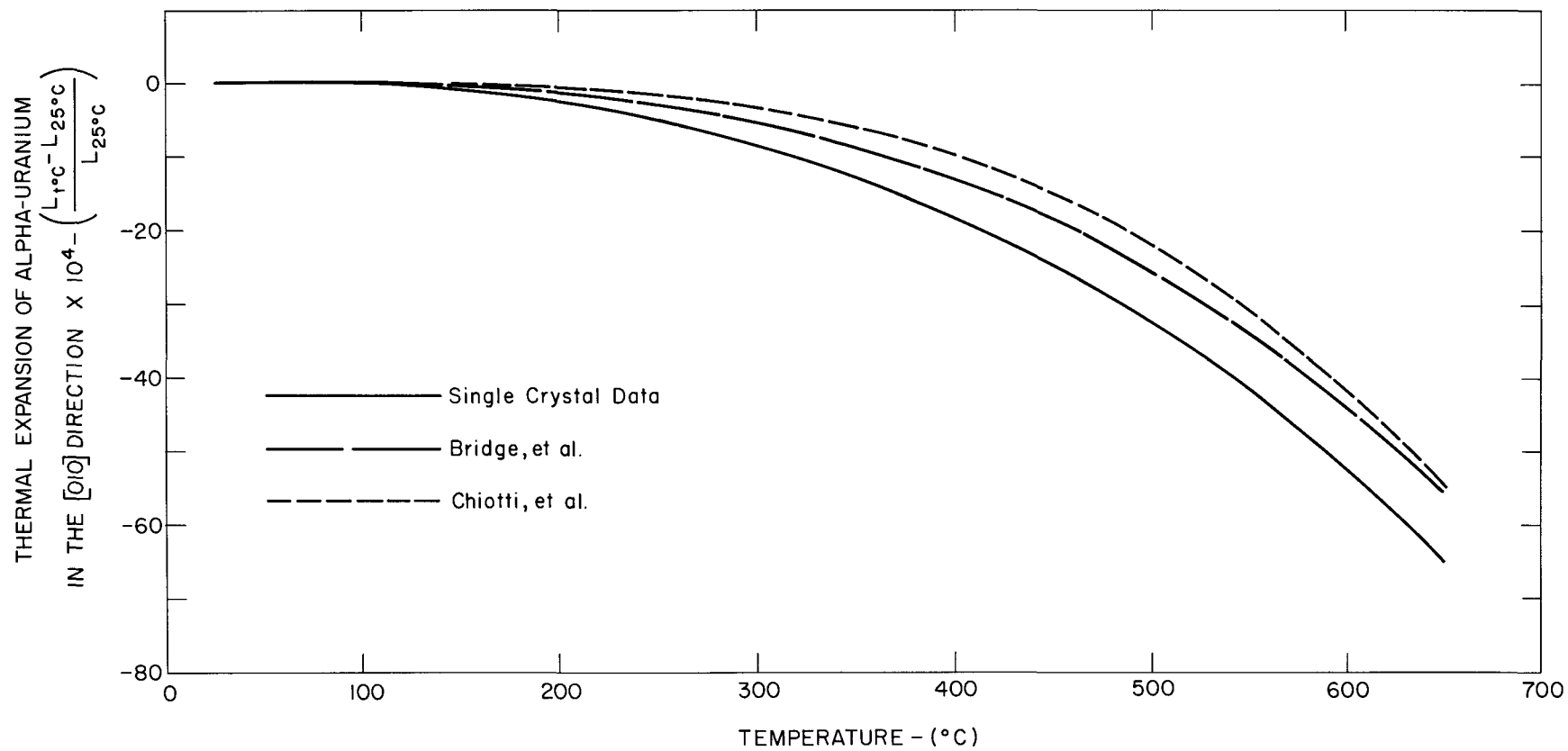


Figure 7

THERMAL EXPANSION OF ALPHA-URANIUM IN THE [001] DIRECTION

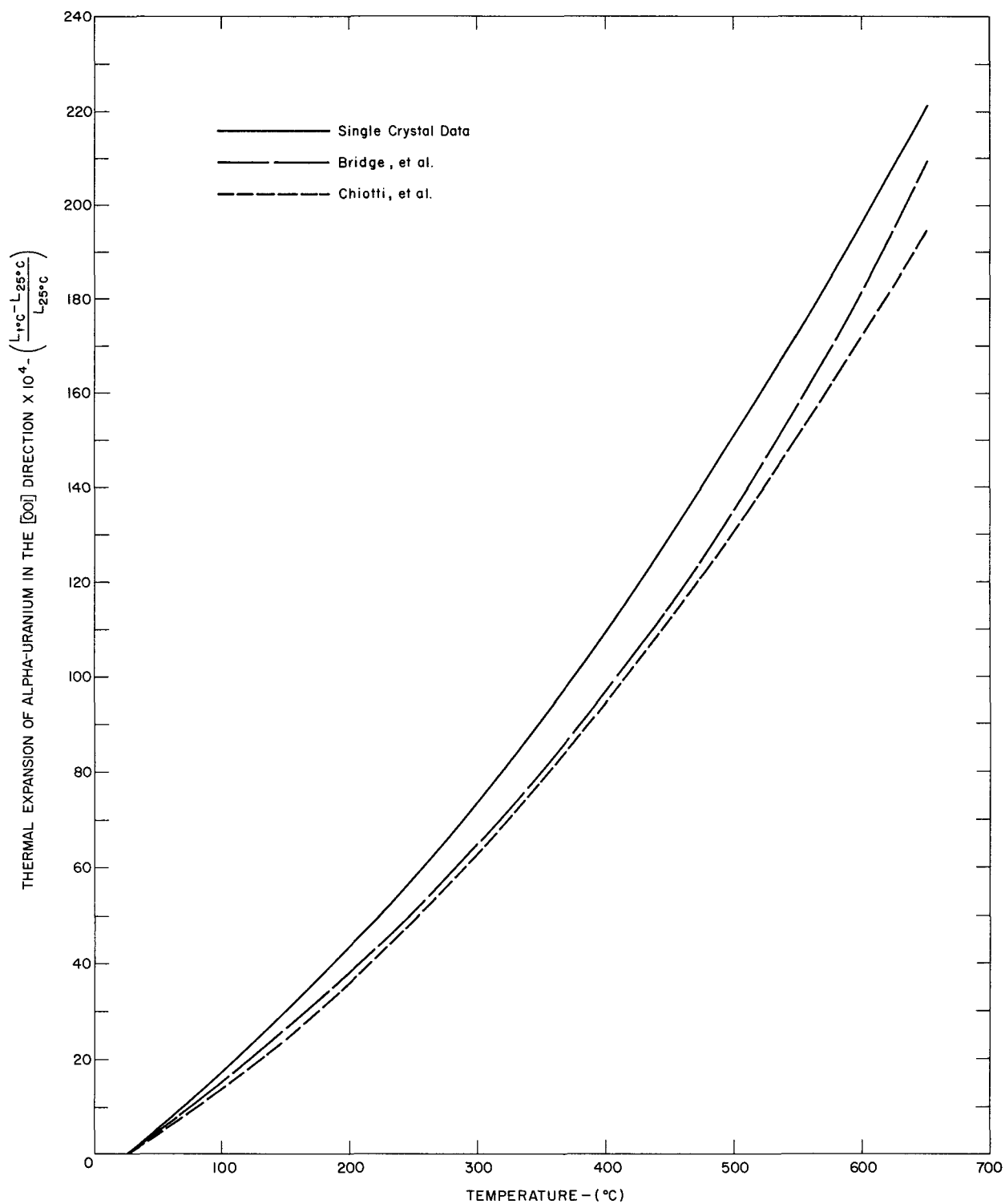


Figure 8
VOLUMETRIC THERMAL EXPANSION OF ALPHA-URANIUM

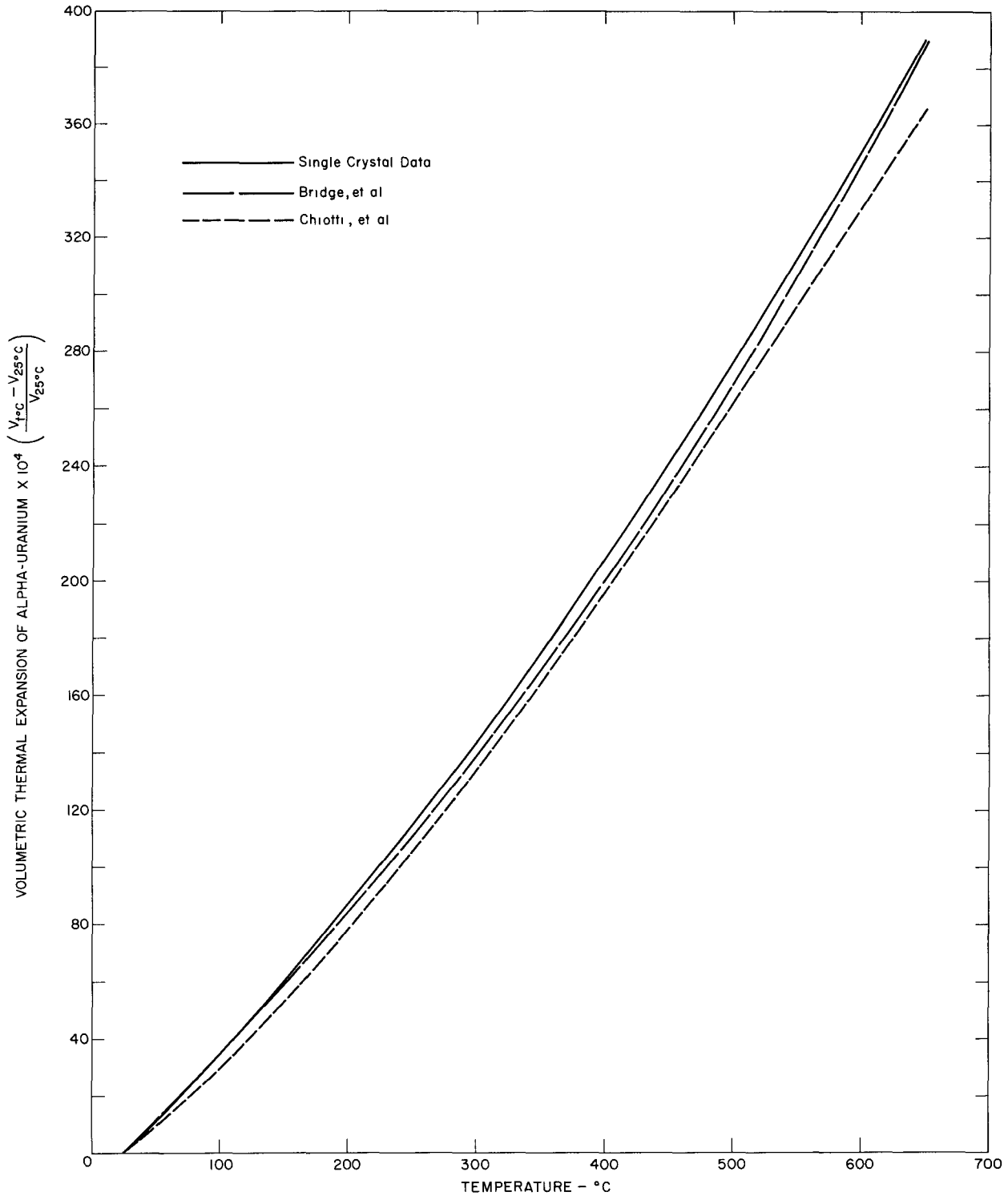


Figure 9

THERMAL EXPANSION OF CRYSTAL 219-2

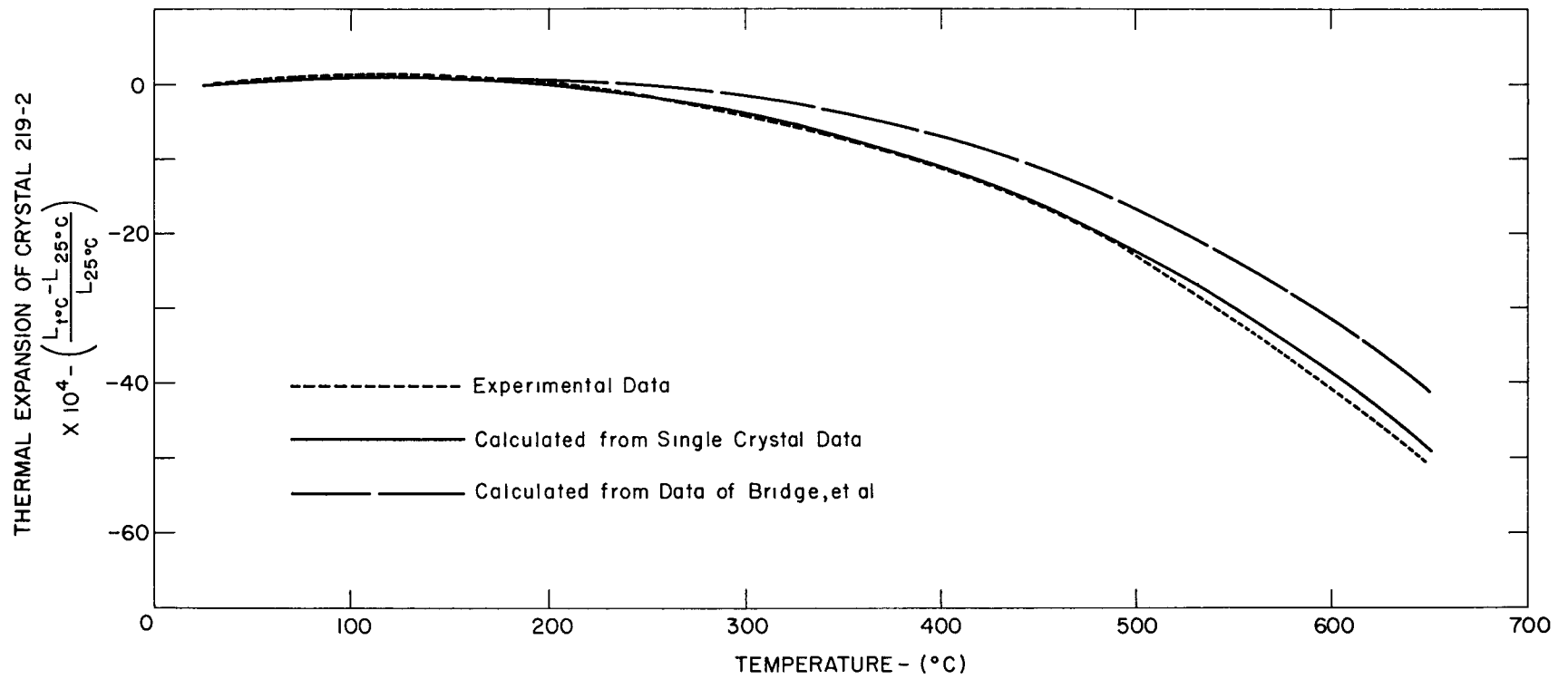


Figure 10

THERMAL EXPANSION OF CRYSTAL 235-B

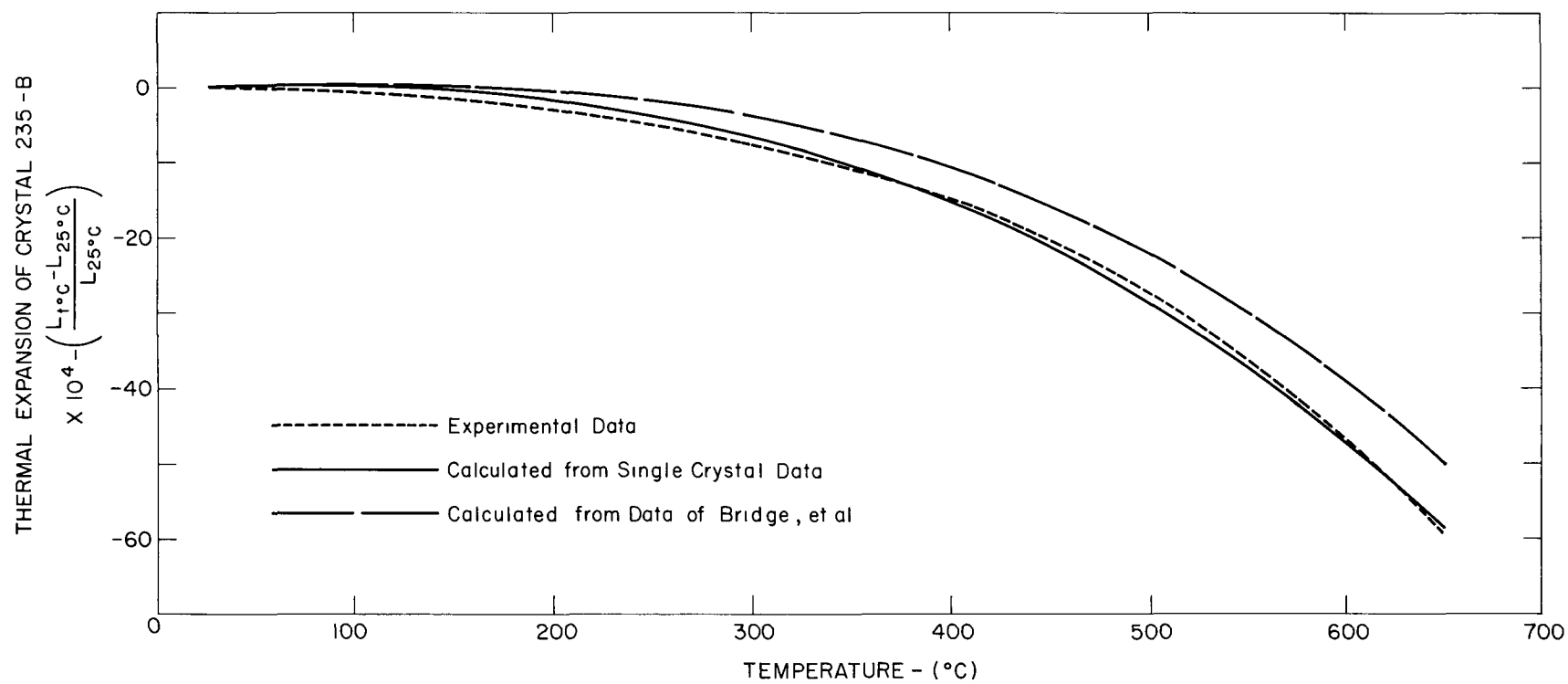


Figure 11

THERMAL EXPANSION OF CRYSTAL 240-A

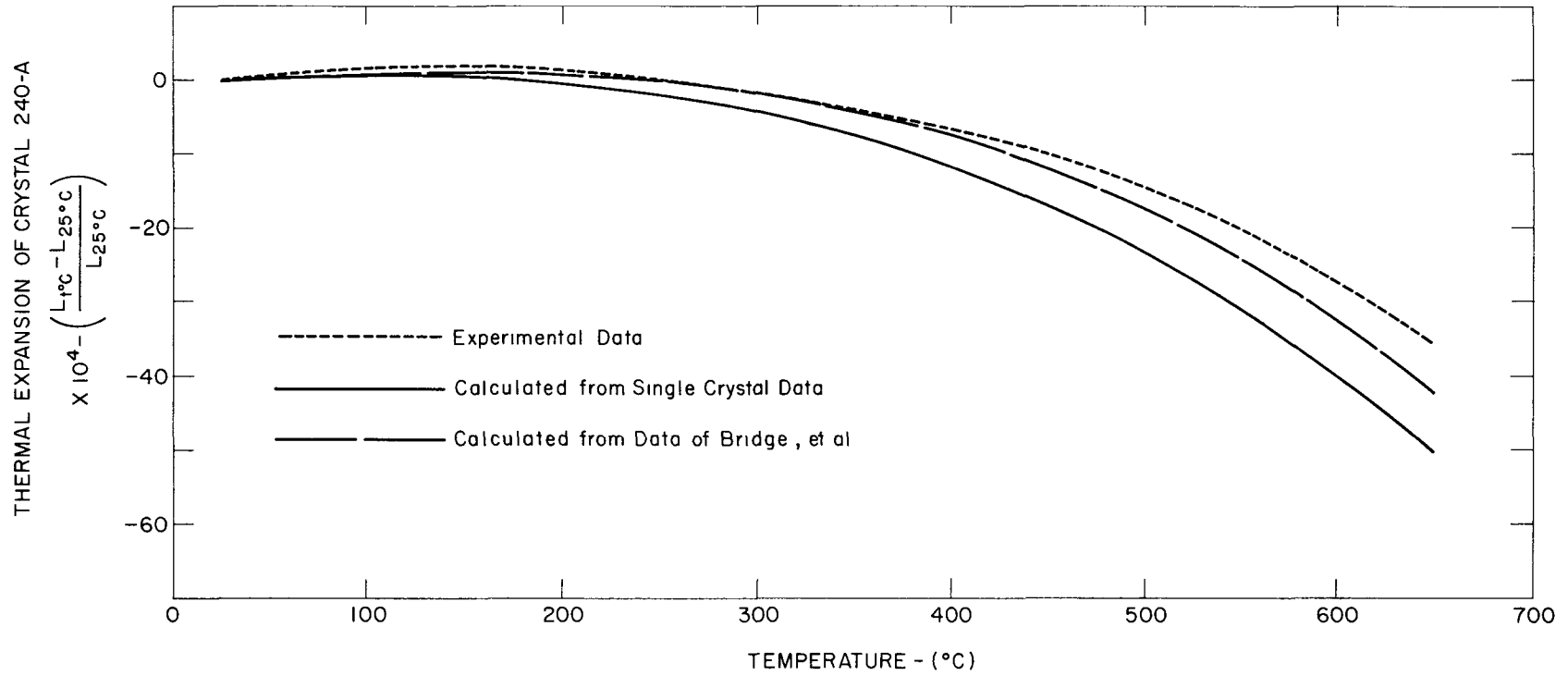


Figure 12

THERMAL EXPANSION OF CRYSTAL 240-B

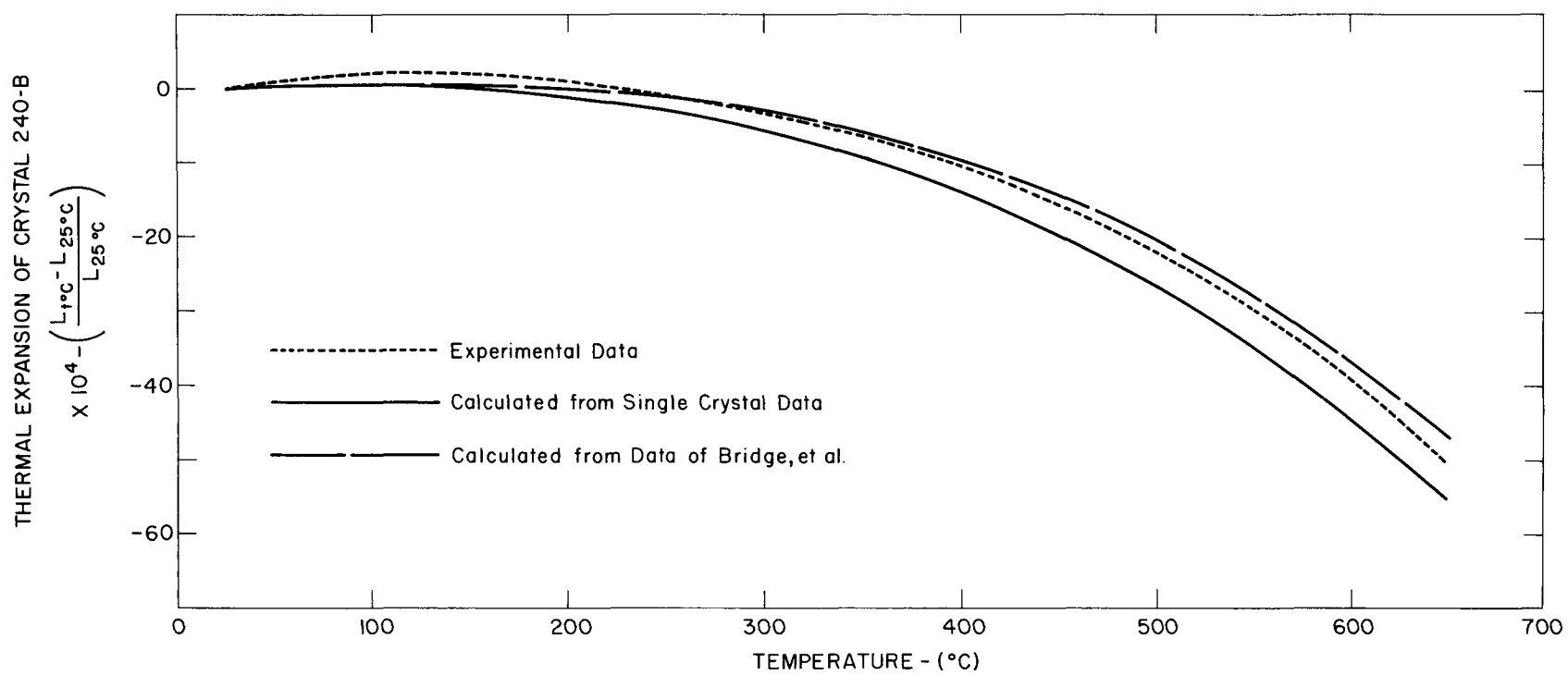


Figure 13

THERMAL EXPANSION OF CRYSTAL 240-C

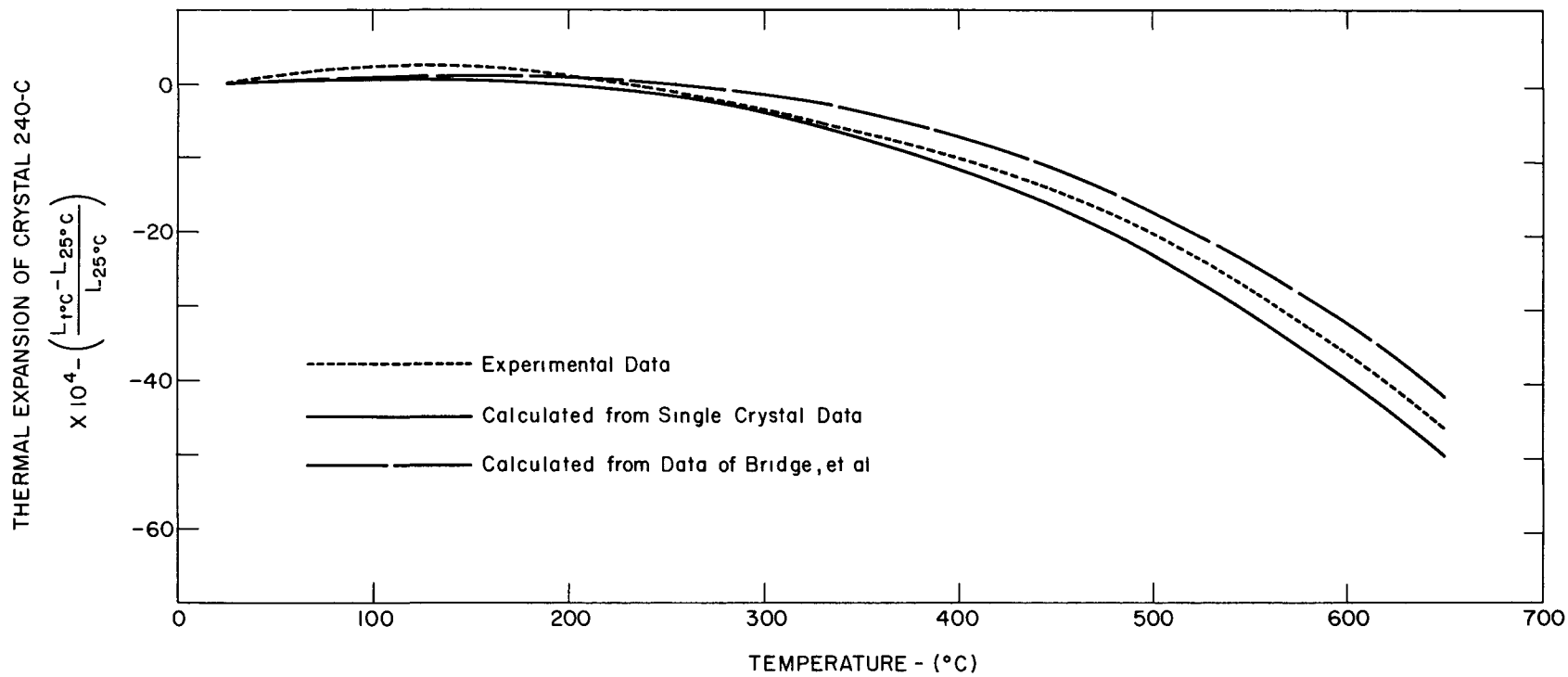


Figure 14

THERMAL EXPANSION OF CRYSTAL T_G 