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An Evaluation of the Statistical Variability in Coefficient of Thermal Expansion Properties of SA-508 and Alloy-600

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Section	Pages	Revision	Date	Comments
All	All	0	10/17/08	Initial Issue
2,3	2-2, 2-3, 3-1. 3-2	1	12/24/08	Revised to delete PMIC data for SA-508 from analysis
3	3-3, 3-4, 3-5, 3-13, 3-14			Revised to address strain hardened A-600 retests
4	4-1			Revised conclusions for above changes
Appendix	A-1 to A-6			New Appendix: justification for excluding PMIC SA-508 data

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1.0 INTRODUCTION

The ASME B&PV Code (Section II) [1] provides material properties for use in design and analysis of pressure vessels and other components, including thermo-physical properties such as thermal expansion, thermal conductivity and thermal diffusivity. Variability in these properties is recognized, and the Code states that these properties are considered typical, and should be considered to have an associated uncertainty of ±10% [1, 2]. However, the meaning of this uncertainty range is not defined in statistical terms.

The purpose of this report is to document a statistical evaluation of Coefficient of Thermal Expansion (CTE) data for SA-508 Grade 2 and thermally treated Alloy-600 tube material. Data obtained from a number of sources are included in the evaluation, including literature sources as well as extensive new laboratory CTE data developed specifically for this purpose. The evaluation results in recommended statistical distributions of this property for the two materials.

This study was performed to support the technical justification for re-defining the primary pressure boundary from the tube-end weld to the hydraulic expansion joint in Westinghouse designed steam generators with hydraulically expanded tubing. Because this technical justification relies significantly on differential thermal expansion between the tube and the tubesheet, and regulatory acceptance criteria are stated in terms of probabilities, it is necessary to establish the mean and probabilistic variability of the CTE.

2.0 CTE DATA AND DATA SOURCES

Figures 2-1 and 2-2 present compilations of CTE data for the two materials compared to the current ASME Section II curve with ±10% error bands. Data are reported from various sources listed in the figure legends and represent mean CTE between 70°F and the plotted temperature. A summary of the various data sources is provided in Table 1.

Data were obtained from several literature sources, as identified in Table 1. The current ASME Section II design curves are assumed to represent a single data set, even though they likely represent means of several data sets. In addition to the literature data, the analyses considered extensive new CTE testing performed specifically for this program under contract to Westinghouse by ANTER laboratories [5]. These tests included multiple samples from nine heats of Alloy-600 steam generator tubing plus four heats of A-508 low alloy steel. The Alloy-600 heats were tested in both the as-received form as well as in a strain hardened condition performed to simulate that produced by hydraulic tube expansion. In all, over 100 new CTE tests were performed at ANTER on thirteen heats of material.

Typical plots of the new ANTER data for A-508 and Alloy 600 materials are contained in Figures 2-3 and 2-4.

Table 1-1 Sources of CTE Data Used in the Evaluation

Alloy-600:	**SA-508 Grade 2:**
Literature Data Sources:	**Literature Data Sources:**
ASME Section II, 2007 Edition [1] Specialty Metals Datasheet [3] Aero SM Handbook [3] Mil Handbook 5 [3] NSMH Values[3] Miscellaneous Datasheets [3] ANL ANTER [7] ANL PMIC [6]	ASME Section II, 2007 Edition [1] ANL ANTER [7]
New ANTER Data [5]:	**New ANTER Data [5]:**
9 heats (3 to 4 samples each) Multiple Tests (single sample) Strain Hardened Specimens (Same 9 heats, 3 to 4 samples each)	4 heats (10 samples each) Multiple Tests (single sample)

An additional dataset for SA-508, provided by ANL and tested at Precision Measurements and Instruments Corporation (PMIC) in both air and vacuum [6], was found to be highly inconsistent with the balance of the data for this material. An assessment of these data was performed, starting with the raw data, and is documented in Appendix A. This assessment concluded that there are anomalies in the data that make it virtually unusable, and that dataset was therefore excluded from this analysis.

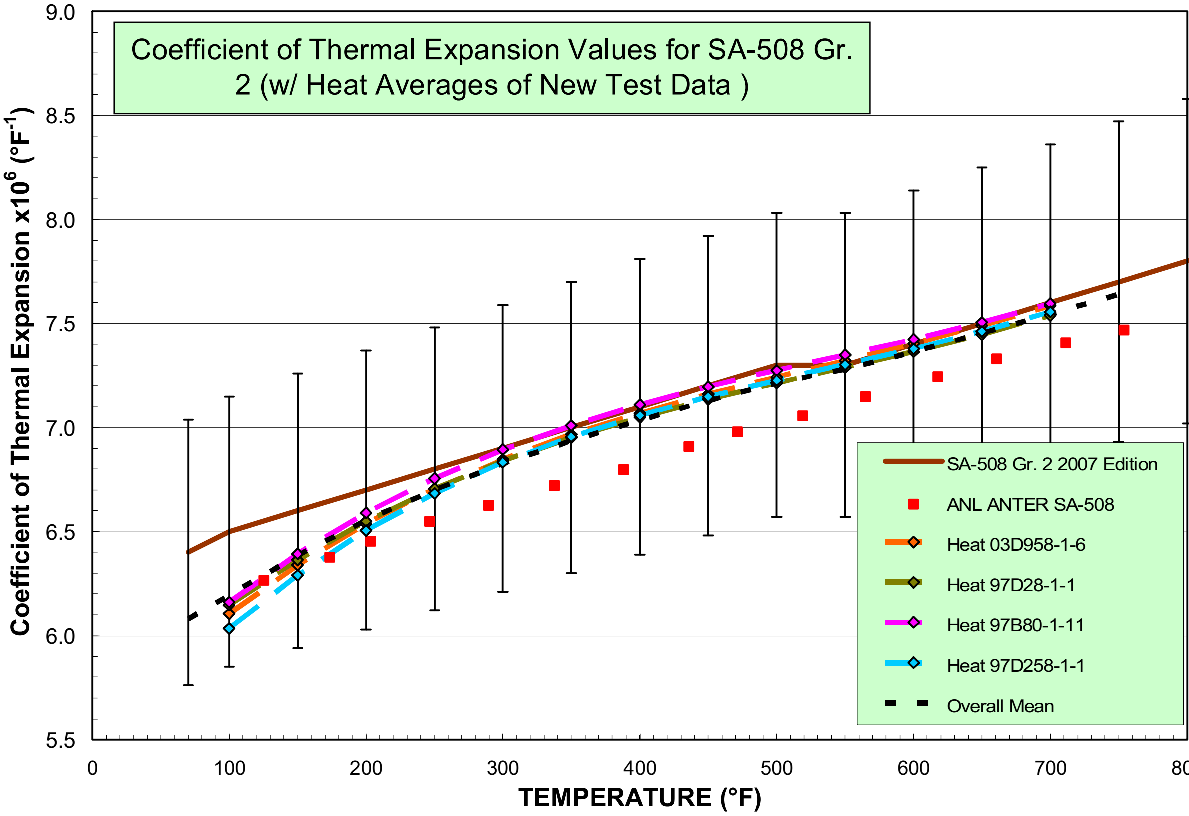


Figure 2-1. CTE Data from various sources for A-508 Low Alloy Steel

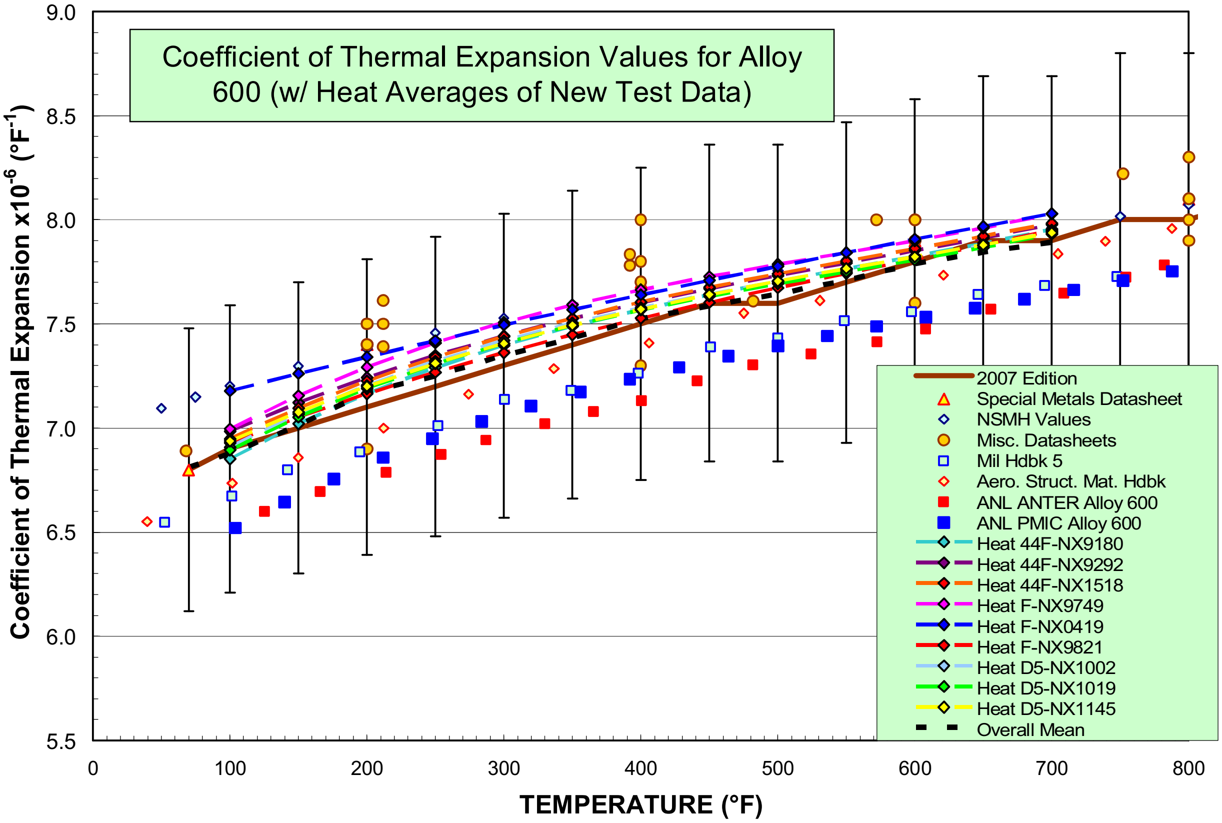
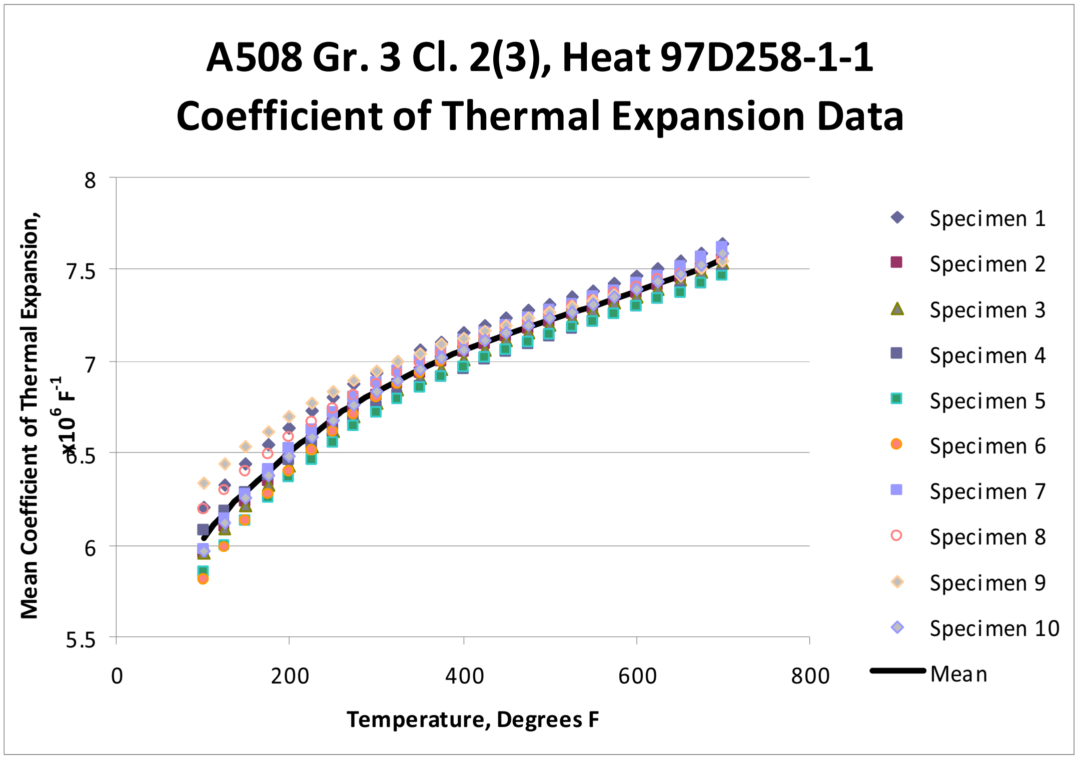


Figure 2-2. CTE Data from Various Sources for Alloy 600



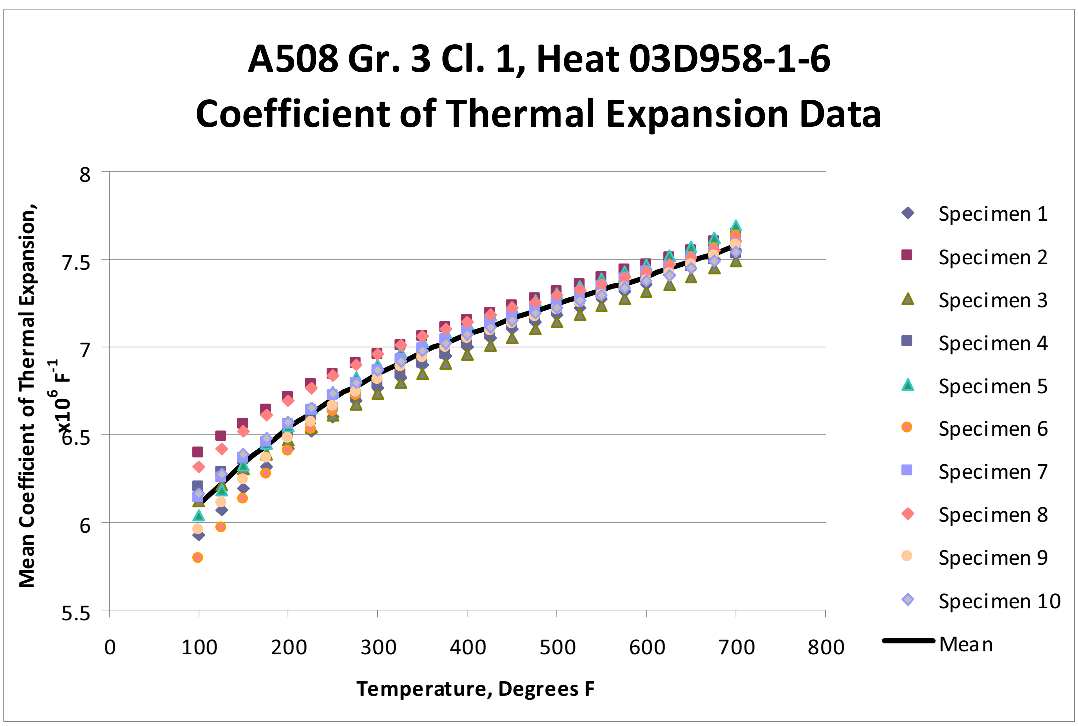
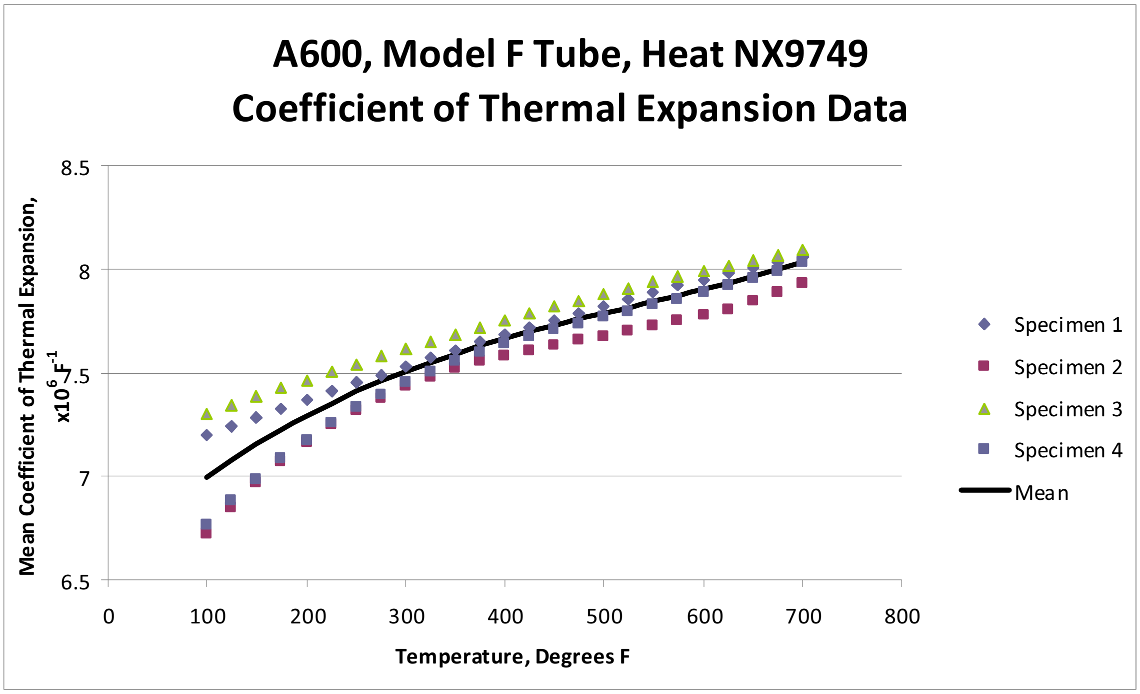


Figure 2-3. Plots of New ANTER Data for Two Heats of A-508 (Typical)



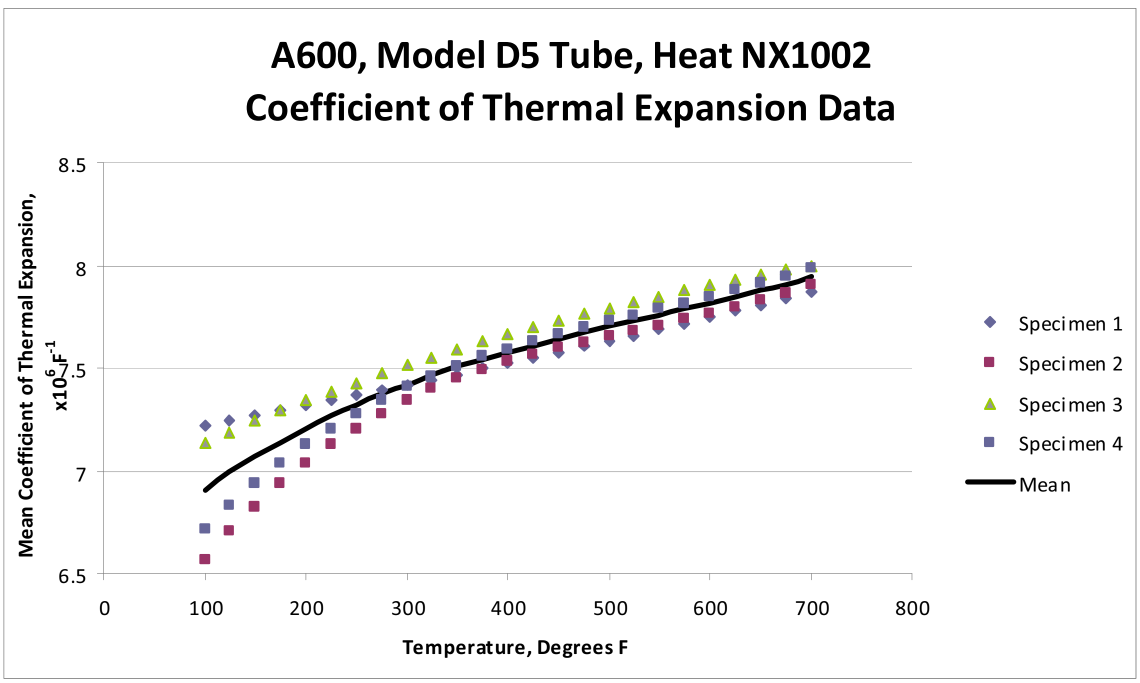


Figure 2-4. Plots of New ANTER Data for Two Heats of Alloy 600 (Typical)

3.0 ANALYSES

3.1 Statistical Analysis of Uncertainties

The data in Figures 2-1 and 2-2 were evaluated using a standard probability plotting technique [4], which is a graphical technique for assessing whether or not a data set follows a given distribution such as normal or lognormal. The CTE data were assessed in terms of their deviations (or residuals) from the overall means of the data for each material at the applicable temperature. Data points were selected at approximately 50°F intervals for each curve, in the temperature range of interest (70°F to 700°F).

The residuals between each individual data point and the applicable overall mean of the data were computed, sorted and plotted as a probability plot in which:

- Vertical axis: Ordered residual values
- Horizontal axis: Order statistic medians for the distribution
  [e.g. Norm Inverse of F; where F = (n - 0.3) / (N + 0.4); N is the total number of data points, and n is the nth data point in the ordered set]
- Analyzed each material individually (A-600: 227 points; SA-508: 82 points)
- Probability plots were developed in this manner for normal and log normal distribution types for each material.

The normal probability plot, generated from the SA-508 dataset of Figure 2-1 (82 data points) is illustrated at the top of Figure 3-1. The correlation coefficient associated with a linear fit to the data is 0.8958, and the mean of the data is very close to zero (0.00044), indicating a good fit to a normal distribution. A lognormal probability plot of the same data is also illustrated at the bottom of Figure 3-1. Review of the two plots indicates that the lognormal distribution gives essentially the same correlation coefficient (0.8964). The normal distribution is recommended because physical data such as CTE are expected to be normally distributed and because the log normal fit introduces the added complexity of having to adjust the original data set to eliminate logarithms of negative numbers (approximately half of the residuals are negative).

The resulting normal distribution for SA-508 is illustrated, along with the residual data, in Figure 3-2. The standard deviation of the residuals is 0.099 x 10-6 in/in/°F, or 1.44% of the mean CTE value for the material at the midpoint temperature (Mean CTE at 400°F = 7.035 x 10-6 in/in/°F).

A similar normal probability plot, generated from the Alloy 600 dataset of Figure 2-2 (227 data points) is illustrated at the top of Figure 3-3. The correlation coefficient associated with the linear fit to the data is 0.9325, and the mean of the data is again close to zero (0.014), indicating a good fit to a normal distribution. A lognormal probability plot of the same data is also illustrated at the bottom of Figure 3-3. In this case the lognormal distribution is a worse fit (correlation coefficient = 0.8909). The normal distribution is again recommended.

The resulting normal distribution for Alloy 600 is illustrated, along with the residual data, in Figure 3-4. The standard deviation of the residuals is 0.175 x 10-6 in/in/°F, or 2.33% of the mean CTE value for the material at the midpoint temperature (Mean CTE at 400°F = 7.525 x 10-6 in/in/°F).

3.2 Evaluation of Within-Heat Variability

Examination of the detailed ANTER test data in Figures 2-3 and 2-4 indicates that there was considerable variability in the test results from different samples from the same heats of material, especially at low temperatures (below ~300°F). This "within-heat" variability was not included in the foregoing statistical analyses, because it was judged to be the result of measurement inaccuracy, and not a true material variability, especially at the lower temperatures, in which the amount of physical growth of the samples from 70°F to the indicated temperature challenged the measurement accuracy of the test equipment. Based on this judgment, the data plots in Figures 2-1 and 2-2 and the statistical analyses of Section 3.1 utilized the mean curves of the new ANTER data for each heat of material.

In order to confirm this judgment, a series of additional tests was run, in which a single sample from one heat each of the two materials was tested multiple times to obtain an estimate of testing uncertainty. The results of these "multiple" tests are compared to the prior "multi-sample" results for the same heats in Figures 3-5 and 3-6. It is seen from these figures that the variability in the multiple tests was essentially equivalent to that of the multi-sample tests. Standard deviations of the data at two temperatures (100°F and 600°F) are indicated in the figures and are comparable for the two cases. Also apparent in the figures is significantly greater variability in the lower temperature regime due to the aforementioned higher measurement uncertainty there. (e.g. Figure 3-7, the standard deviations at 100°F are more than three times those at 600°F).

Based on these additional tests, and the data comparisons presented in Figure 3-7, is concluded that the within-heat variability observed in the multi-specimen test data is solely attributable to testing uncertainty, and that utilizing the heat means in the statistical analyses of Section 3.1 is an appropriate approach.

3.3 Effect of Strain Hardening on Alloy-600 CTE

A second set of Alloy 600 specimens were machined from the same nine heats of tubing material, but these were hydraulically expanded into split collars, sized to be typical of the tubesheet bore diameter, before CTE testing, to simulate the strain hardening that occurs in tubesheet ends of steam generator tubes hydraulically expanded into the tubesheet as applied in Westinghouse steam generators.. The apparent strain hardening effect on CTE from this initial set of tests is illustrated in Figure 3-7. It is seen from this figure that the variability is about the same in the strain hardened versus non-strain hardened data, but that the means of the strain hardened data tended to be somewhat lower than those in the non-strain hardened results, especially in the higher temperature regime (open data points versus solid points connected by dashed lines in Figure 3-7).

Cold working during hydraulic expansion, however, creates a large increase in dislocation density. Dislocation interactions during deformation create interstitial atoms and vacancies in the atomic lattice. At 600°F, dislocations, interstitials and vacancies tend to rearrange themselves via diffusion. Vacancies and interstitials mostly disappear and dislocations form relatively stable networks. It was thus hypothesized that this effect caused the downward shift in CTE values at temperatures above 350°F in the initial thermal expansion tests of cold worked tubing, and that retesting might yield results more closely resembling the non-strain hardened results, since the specimens will have been heated to >600°F (simulating to the first cycle of steam generator operation after hydraulic expansion). Under this scenario reheating to 600°F would not lead to further changes in CTE.

To test this hypothesis, the samples from three of the strain hardened heats of Alloy 600 tubing were retested using identical equipment and procedure as the initial strain hardened tests. The results are illustrated in Figure 3-8, which contains three CTE plots for each of the retested Alloy 600 heats. Examination of this figure indicates that the repeat strain hardened test results, in all cases, lie on or very close to the original, non-strain hardened data, thus confirming the above hypothesis. In the cases where there is a small deviation in the test results, the repeat strain hardened tests fell above rather than below the original non-strain hardened results, and were much closer to the non-strain hardened results at the higher temperatures which are of primary interest.

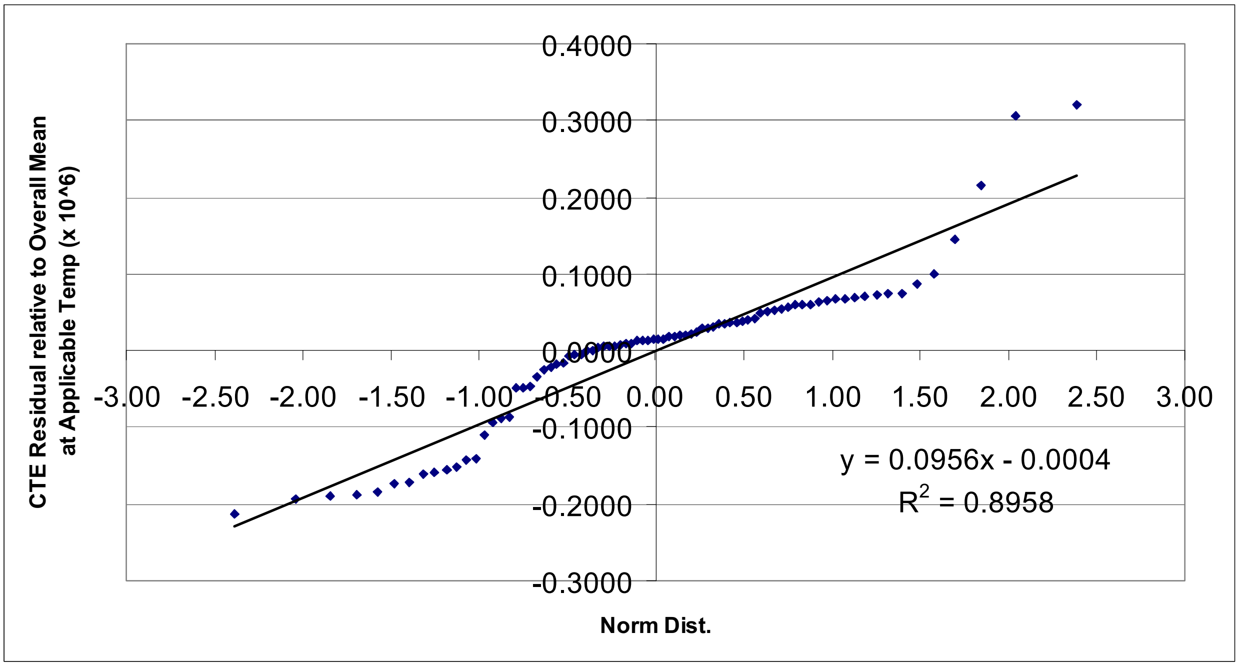
The direction of cold working has no effect on the density of dislocations, interstitials and vacancies that are produced by the cold work. Since the repeat tests demonstrated essentially no effect of cold work on CTE, the results are also independent of cold work direction.

Figure 3-9 is a re-plot of all of the Alloy 600 data, with the non-strain hardened results replaced by the strain hardened results for the three heats that were retested in the strain hardened state. The figure is indistinguishable from Figure 2-2. The statistical analysis discussed in Section 3.1 above was re-performed for Alloy 600 using the data in Figure 3-9 rather than Figure 2-2. The revised statistical distribution, about a new overall mean curve, is virtually identical to that developed based on the non-strain hardened data. (Standard Deviation = 0.176 or 2.34%, Correlation Coefficient of Fit to Normal Distribution = 0.9268).

3.4 Overall Mean versus ASME Code Curves

Review of Figures 2-1 and 2-2 indicates that the ASME Code CTE curves are a reasonable representation of the overall mean curves of the data. For SA 508, the overall mean is consistently about 1% lower than the Code curve for the entire temperature regime, except for at lower temperatures (<300°F), at which it is ~4% lower. Since a higher tubesheet CTE is conservative with respect to steam generator tube to tubesheet interface pressure (results in lower interface pressure), it is deemed reasonably accurate and conservative to continue to use the ASME Code values.

A similar observation may be drawn for Alloy 600, based on both the non-strain hardened data (Figure 2-2) and the strain hardened repeat tests (Figure 3-9). The overall means of the data are consistently higher than or equal to the ASME Code curve except for one small region at 650°F. In this region the Code curve exhibits a discontinuity which is believed to be due to truncating the data to two significant figures, which was done in later Code editions, while the overall mean of the data is a smooth curve. Nonetheless, the difference between the Code curve and the overall mean in this region is very small. Use of a lower tube CTE for the Alloy 600 tubes is conservative with respect to steam generator tube to tubesheet interface pressure (results in lower interface pressure).and thus it is deemed reasonably accurate and conservative to continue to use the ASME Code values.



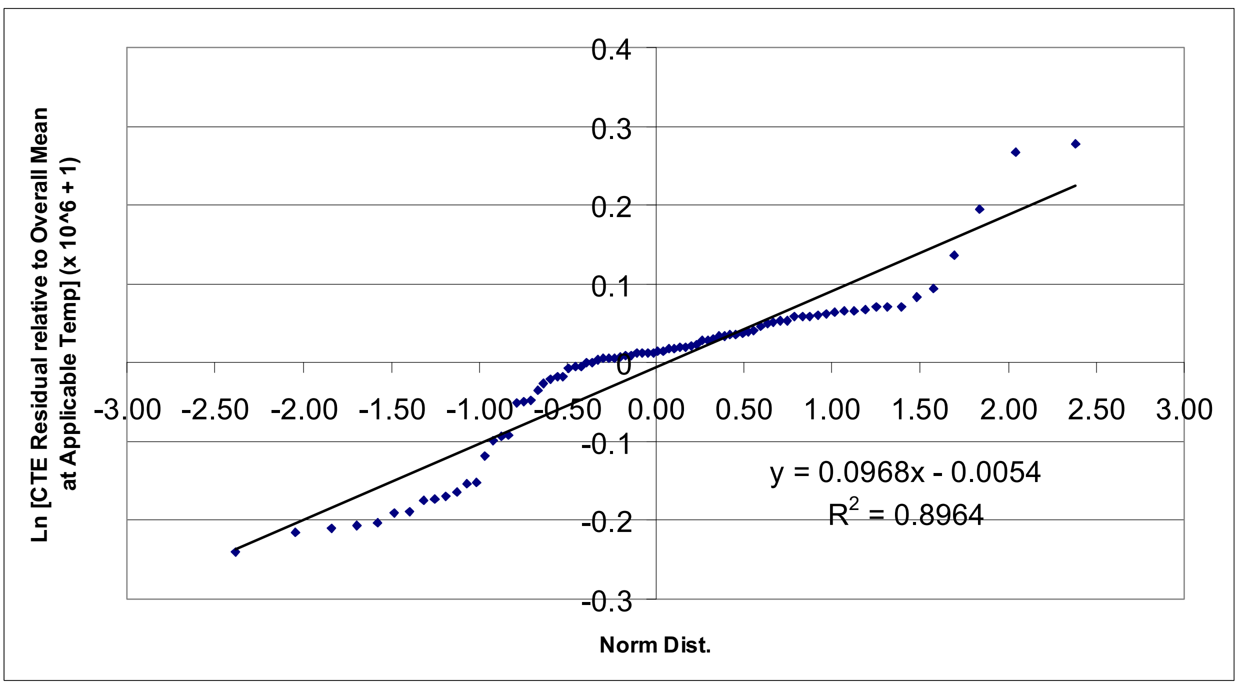


Figure 3-1. Normal and Lognormal Probability Plots for A-508 CTE Residuals and Associated Linear Curve Fits

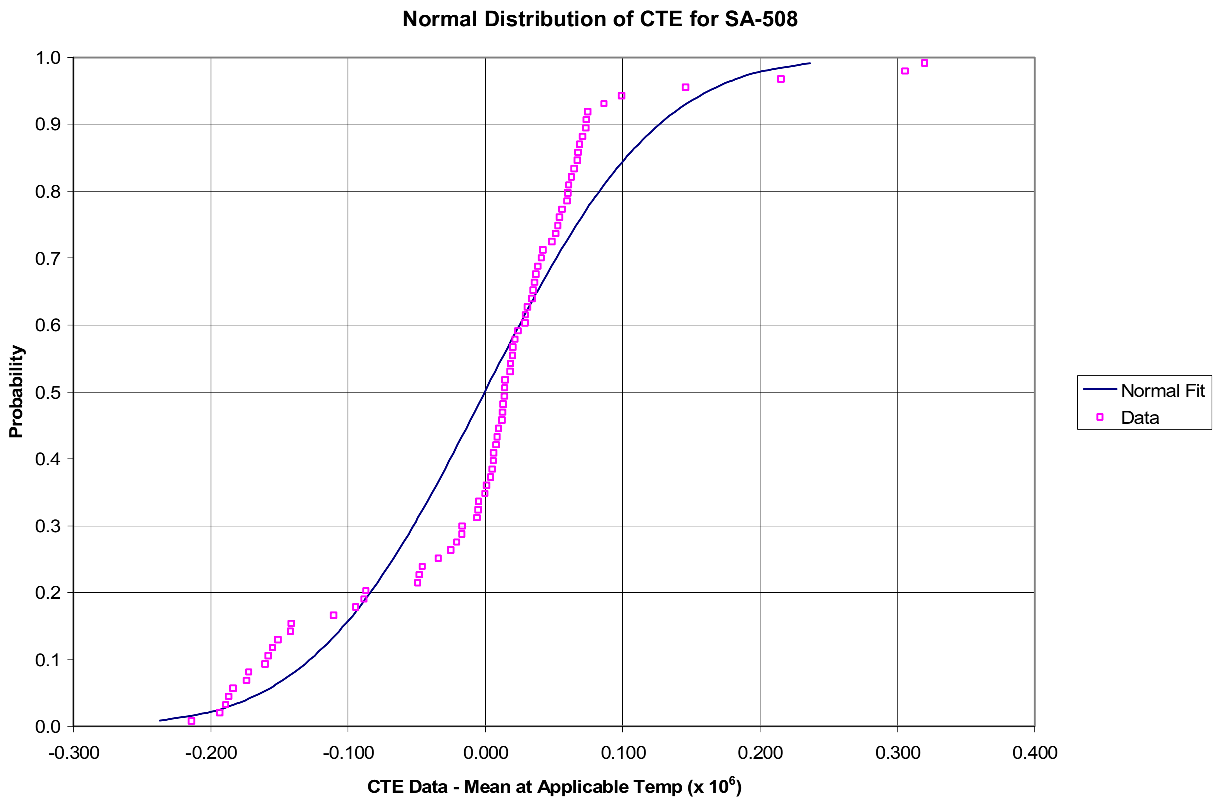
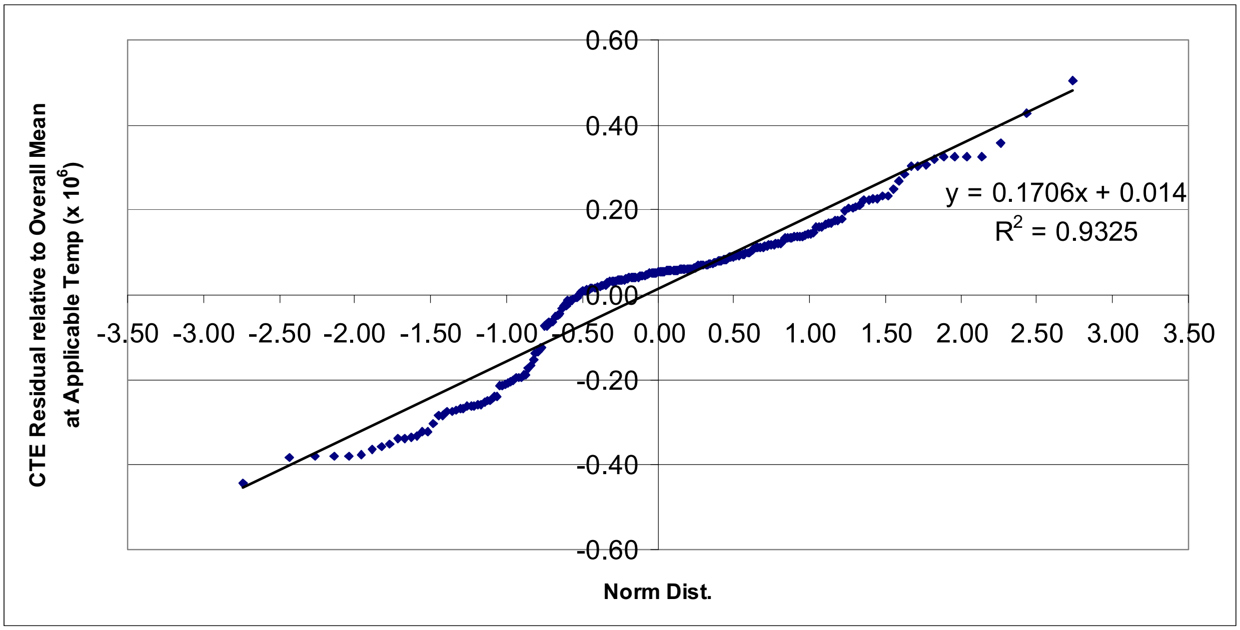


Figure 3-2. Recommended Normal Distribution of CTE Data for SA-508



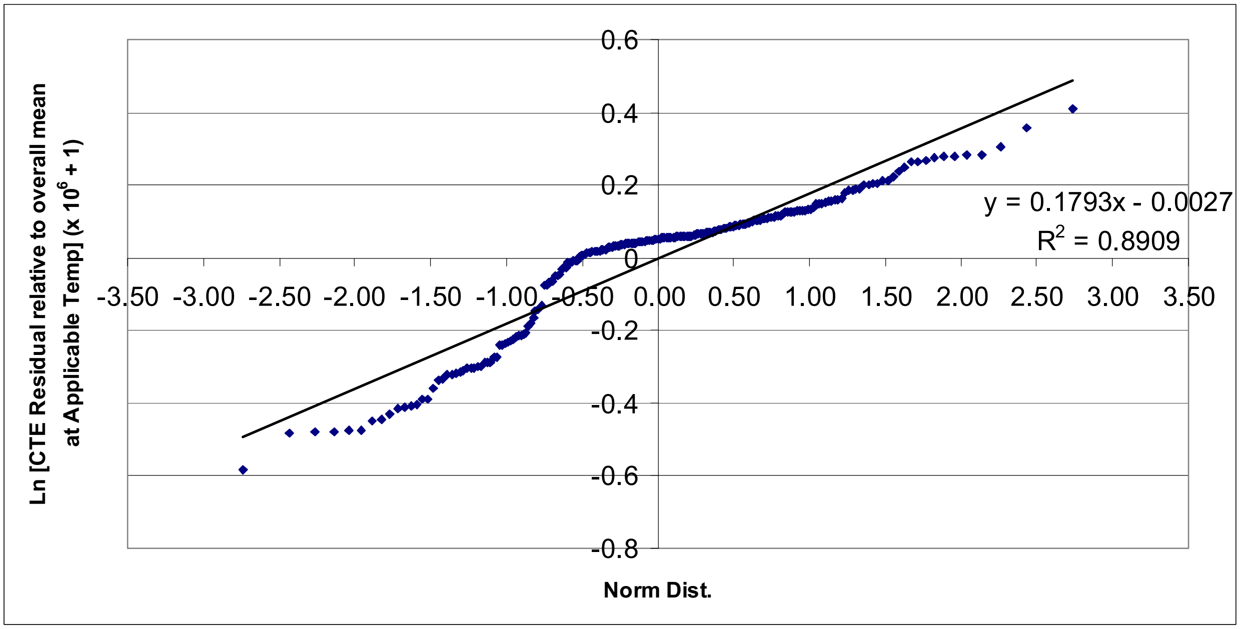


Figure 3-3. Normal and Lognormal Normal Probability Plot for Alloy 600 CTE Residuals and Associated Linear Curve Fit

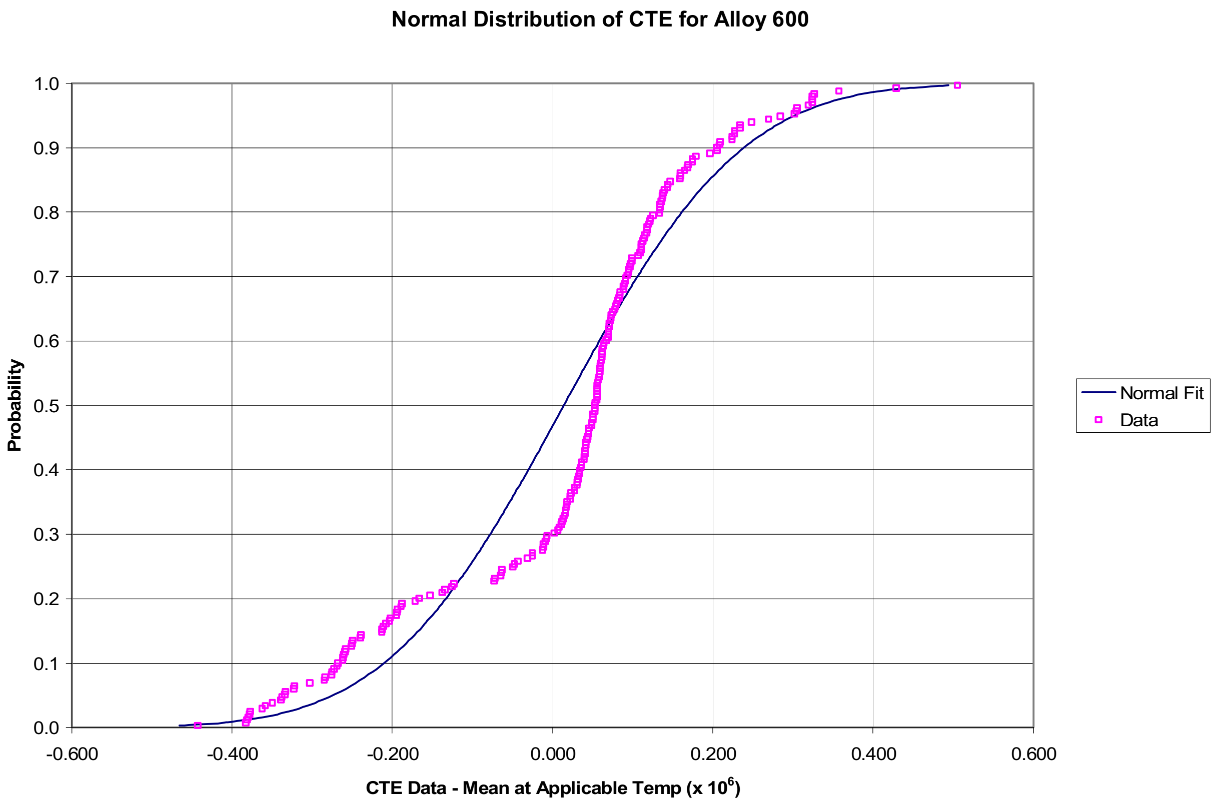
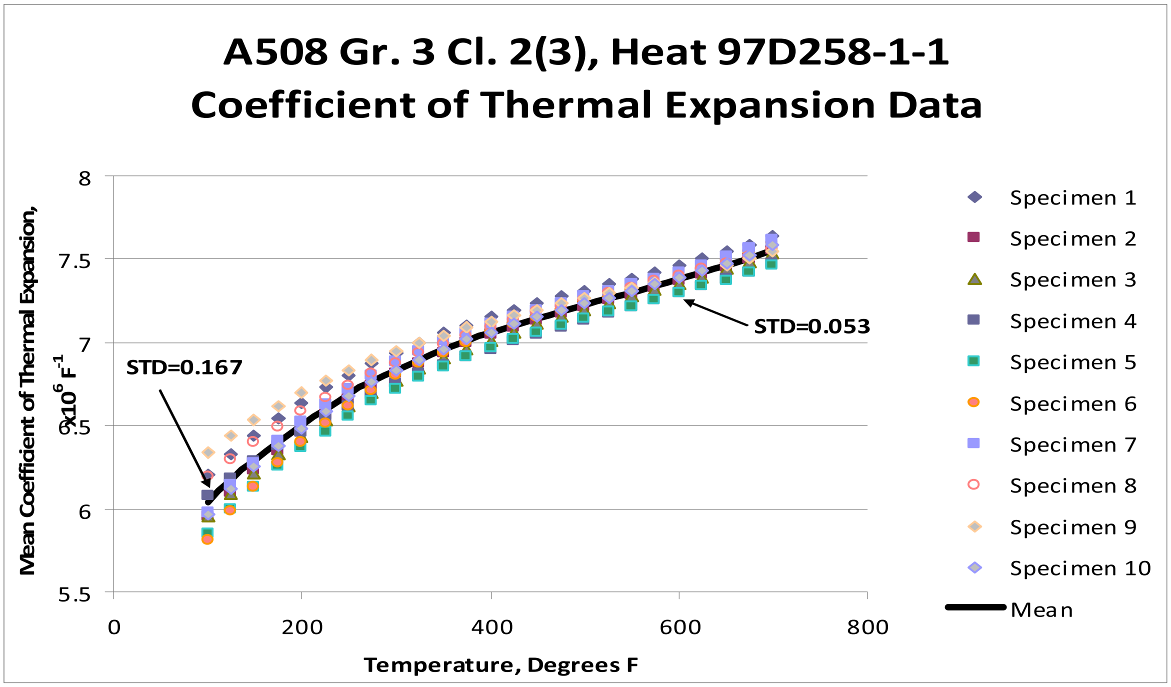


Figure 3-4. Recommended Normal Distribution of CTE Data for Alloy 600



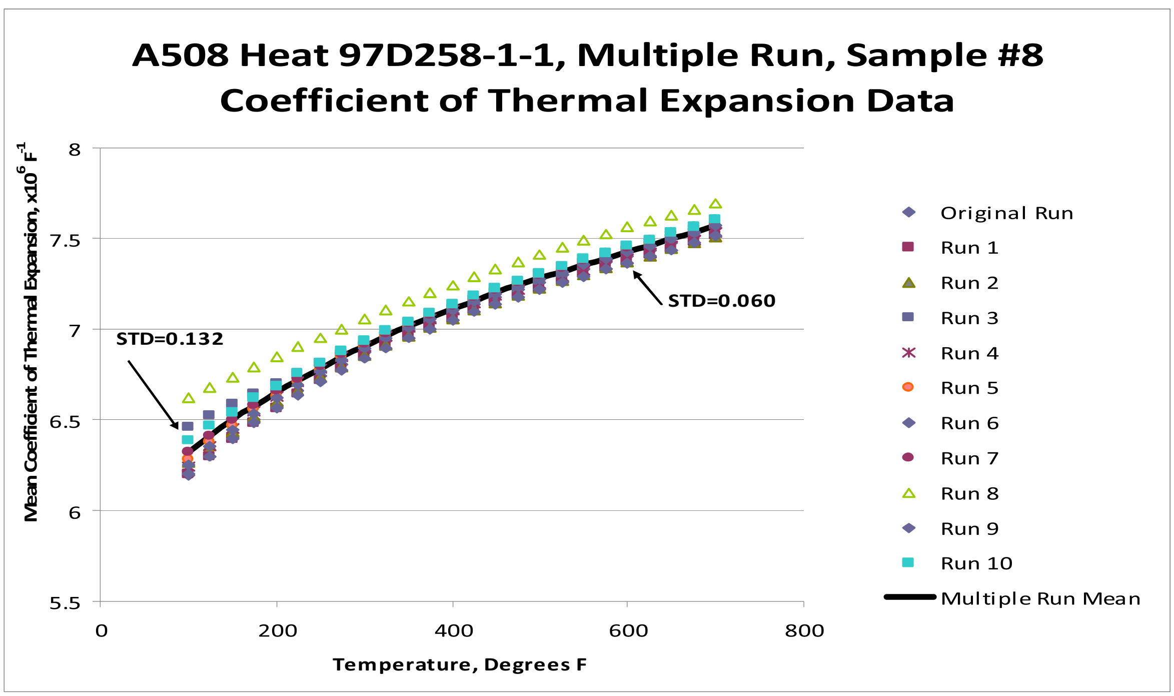
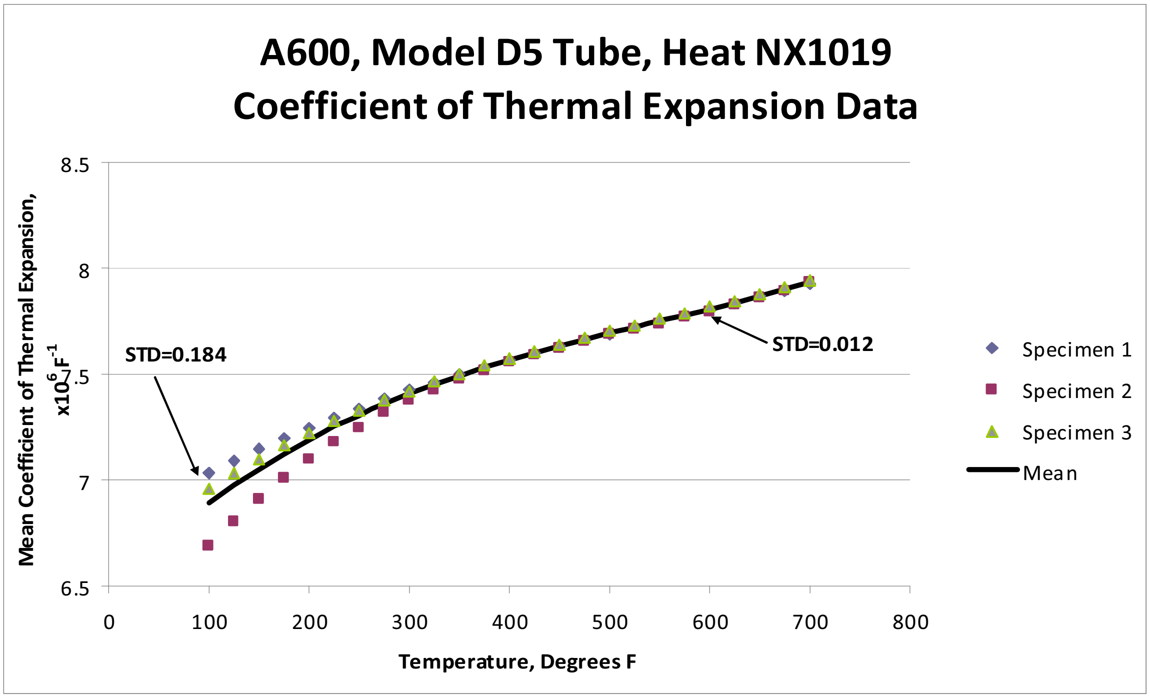


Figure 3-5. Comparison of Within-Heat Scatter of Multi-Sample Tests on a Heat of SA-508 (upper plot) with Multiple Tests of a Single Sample from the Same Heat (lower plot)



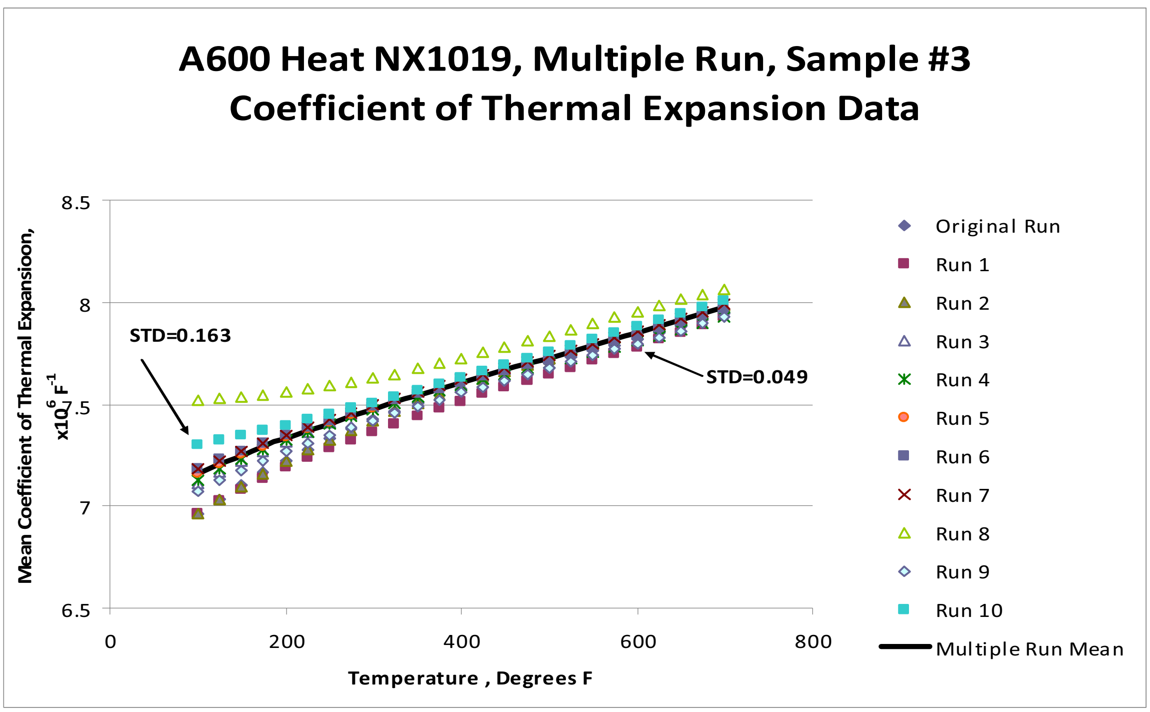


Figure 3-6. Comparison of Within-Heat Scatter of Multi-Sample Tests on a Heat of Alloy 600 (upper plot) with Multiple Tests of a Single Sample from the Same Heat (lower plot)

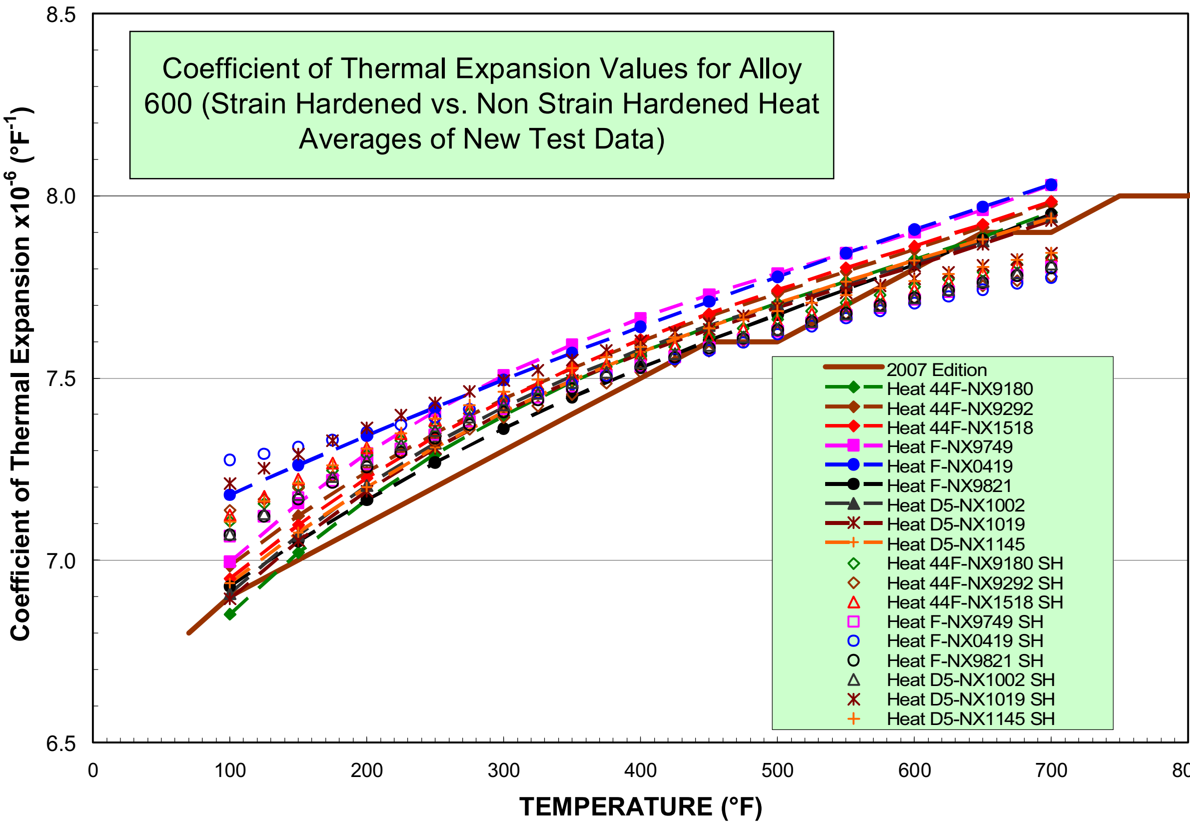


Figure 3-7. Illustration of the Apparent Effect of Strain Hardening on Alloy 600 CTE Data. Heat Means of Strain Hardened versus Non Strain Hardened Data – Initial Testing

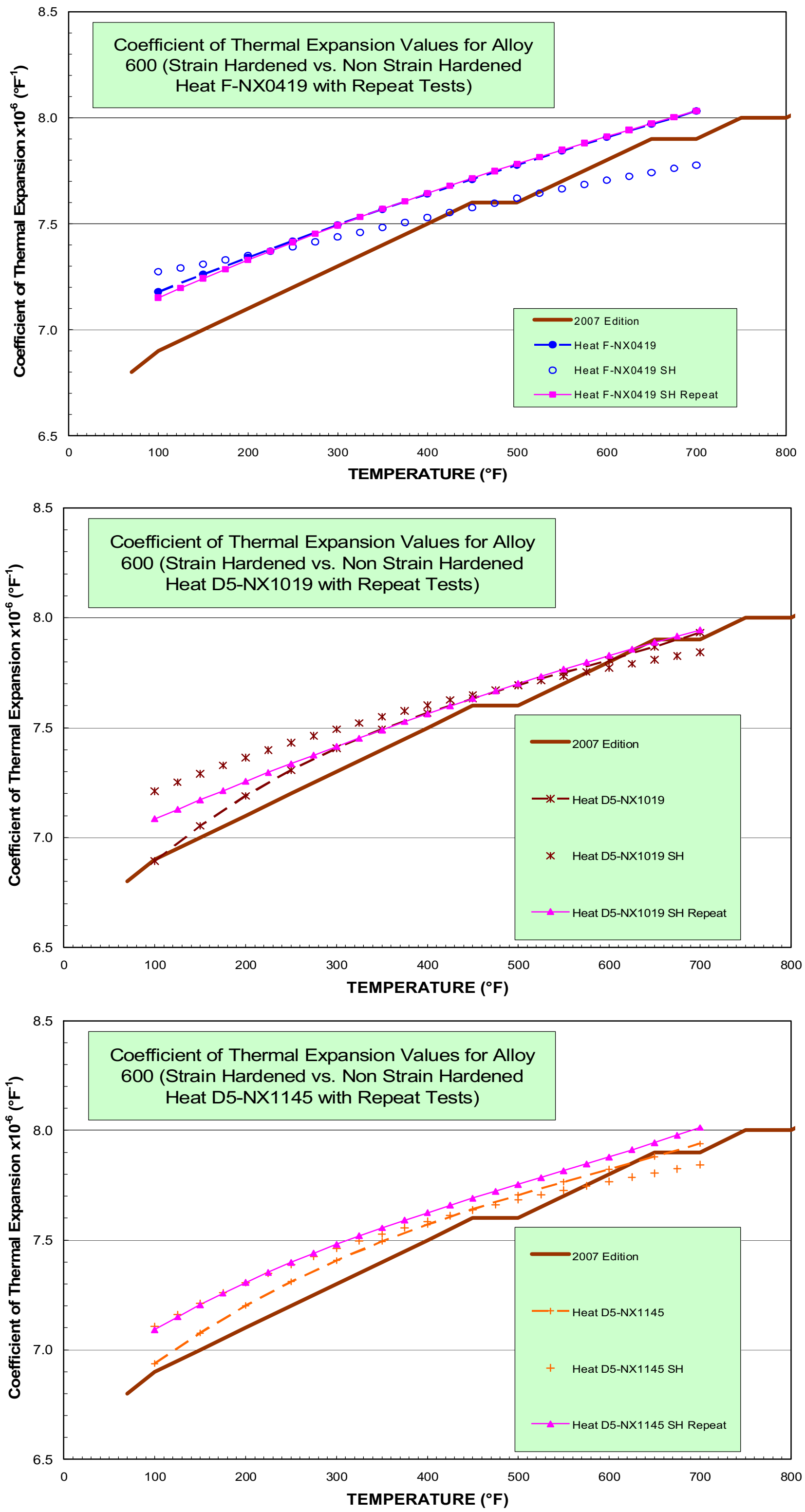


Figure 3-8. Further Study of the Effect of Strain Hardening on Alloy 600 CTE Data: Means of Strain Hardened versus Non Strain Hardened versus Repeat Strain Hardened Tests

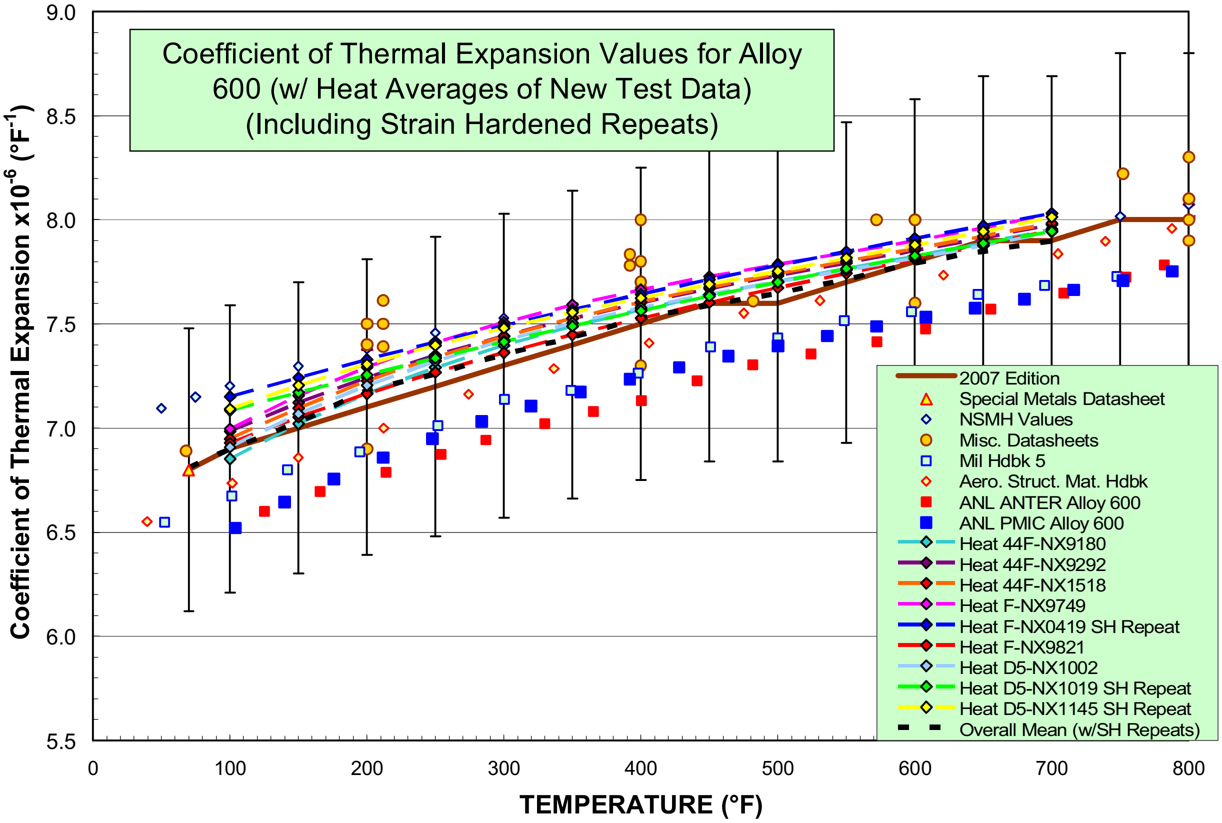


Figure 3-9. Compilation of CTE Data from Various Sources for Alloy 600, with Original Test Data Replaced by Repeat Strain Hardened Test Data (Plot is indistinguishable from Figure 2-2 thus demonstrating that strain hardening has a negligible effect.)

4.0 CONCLUSIONS

The analyses presented in this report result in recommended statistical distributions of CTE for use in Monte Carlo analyses of steam generator tube pullout depths (H*). The recommendation is a normal distribution about the ASME Section II (2007 Edition) curves for SA-508 Grade 2, with a standard deviation of 0.099×10^{-6} in/in/°F, or 1.44% of the Code CTE values. For Alloy 600, the recommendation is a normal distribution with a standard deviation of 0.175×10^{-6} in/in/°F, or 2.33%. In the case of Alloy 600, an evaluation was also performed of the effect of strain hardening due to hydraulic expansion of the tubes into the tubesheet. Strain hardening was found to have a negligible effect on CTE as it was demonstrated that the CTE of the strain hardened specimens returned to its non-strain-hardened value after a single exposure to the typical normal operating temperature, 600ºF.

The study also found that, compared to the overall means of the CTE data, it is reasonably accurate and conservative to use the ASME Code CTE curves [1] for these two materials as the mean values about which the above statistical variations occur. The following table summarizes the recommended values of CTE for use in the probabilistic analysis for H*:

Material	Mean CTE	Standard Deviation
SA-508	2007 Edition of ASME Code, Section II, at desired temperature	1.44% of mean value at desired temperature
A600	2007 Edition of ASME Code, Section II, at desired temperature	2.33% of mean value at desired temperature

.

5.0 REFERENCES

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2. "Thermophysical Properties of Ferrous Structural Alloys", R.A. Moen, Hanford Engineering Development Laboratory, HEDL-TME 78-47, EC-79b,h, April, 1978
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4. Chambers, John, William Cleveland, Beat Kleiner, and Paul Tukey, (1983), "Graphical Methods for Data Analysis", Wadsworth.
5. Transmittals of ANTER Laboratories Test Data, J.T. Kandra to P.C. Riccardella, 7/18/2008 thru 10/10/2008.
6. Precision Measurements and Instruments Corporation, THERMAL EXPANSION MEASUREMENTS OF AN ALLOY 600 TUBE AND A508 STEEL ROD SPECIMEN, Argonne National Laboratory, 7A-09505, September 18, 2007
7. ANTER Laboratories, Inc, TRANSMITTAL OF TEST RESULTS, Transmittal #: PR27988-52336 to Argonne National Laboratory, April 27, 2007

APPENDIX A

RATIONALE FOR EXCLUDING PMIC SA-508 DATA
FROM CTE STATISTICAL EVALUATION

One of the data sets originally used in the CTE statistical evaluation was data obtained from ANL based on testing performed at Precision Measurements and Instruments Corporation [A1]. These data were not consistent with the balance of the data collected for SA-508 low alloy steel. To ascertain the source of the inconsistency, an assessment of these data was performed, starting with the raw data tabulated in Reference [A2]. Two sets of CTE data are presented for SA-508 material in [A2], one for a sample tested in a vacuum and a second for a sample tested in air. The raw data from these tests are plotted in Figure A-1, in terms of measured expansion (in micro-strain) versus temperature in °F. Also shown on the plot are data for the same SA-508 material performed for ANL by ANTER Laboratories Inc [A3], as well as a sampling of more recent CTE tests performed by ANTER for Westinghouse [A4-A6].

Figure A-1 indicates that the data sets tested by ANTER, including both the original tests for ANL as well as the more recent tests for Westinghouse, all lie in a fairly tight band. The PMIC air data deviates from that band at the low temperature end, while the PMIC vacuum data shows an even more significant deviation. Figure A-2 presents an expanded view the low temperature range (0 to 200°F) of the data in Figure A-1. It is seen from this figure that the two sets of PMIC data both exhibit offsets (or dead-bands) at the start of the tests, in which essentially no expansion was measured. The offset in the air data is ~15°F while the offset in the vacuum data is greater than 40°F. Since CTE is generally computed relative to an unexpanded room temperature state (70°F), these offsets have a significant impact on the CTE values computed from the data, especially at the low temperature end. Figure A-3 illustrates this effect, in terms of average CTE between room temperature and the indicated temperature computed from the raw data. It is seen from this plot that the PMIC vacuum data deviates over the entire temperature range, due to the large offset at the start of the test. Based on these observations, it is concluded that the PMIC data vacuum could not be used in the statistical analyses of this report without adjusting for the observed offsets in the raw data.

It was determined in discussions with Argonne National Laboratories, the sponsor of the PMIC CTE tests on the SA-508 material, that the sequence of testing was performed first in vacuum (increasing the temperature then decreasing temperature), then in air. In the initial vacuum test, the material was exposed to a temperature of approximately 700°C. Exposure of the material to this temperature changes the microstructure of the material and invalidates subsequent tests on the same specimen. Therefore, the data for the sample in vacuum taken in the temperature decreasing mode and the air environment data are excluded a priori. The PMIC vacuum data from the increasing temperature tests remains suspect in that the raw data exhibits the large offset at the start of the tests, observed in Figures A-1 and A-2. The resulting CTE computed for this sample thus deviates from the remaining available data for SA-508 by a large degree.

Because of this, and because the new testing performed in support of this effort produced sufficient of data for the statistical analysis, it was decided to exclude the PMIC SA-508 data from the study..

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A1. Precision Measurements and Instruments Corporation, “Thermal Expansion Measurements of an Alloy 600 Tube and A508 Steel Rod Specimen”, Final Report, Argonne National Laboratory Purchase Order Number 7A-09505, September 18, 2007
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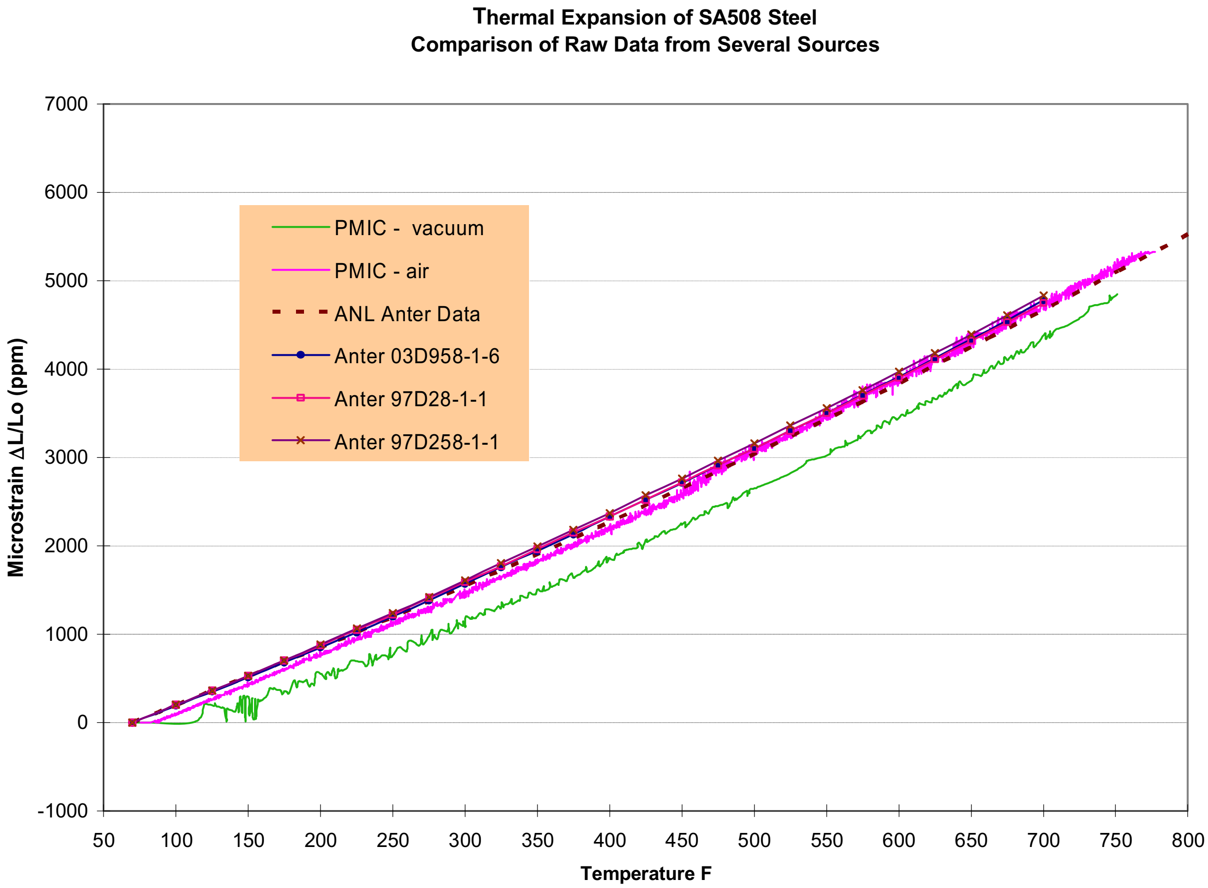

Figure A-1 – Raw Test Data (in Micro-strain) from several SA-508 CTE Tests

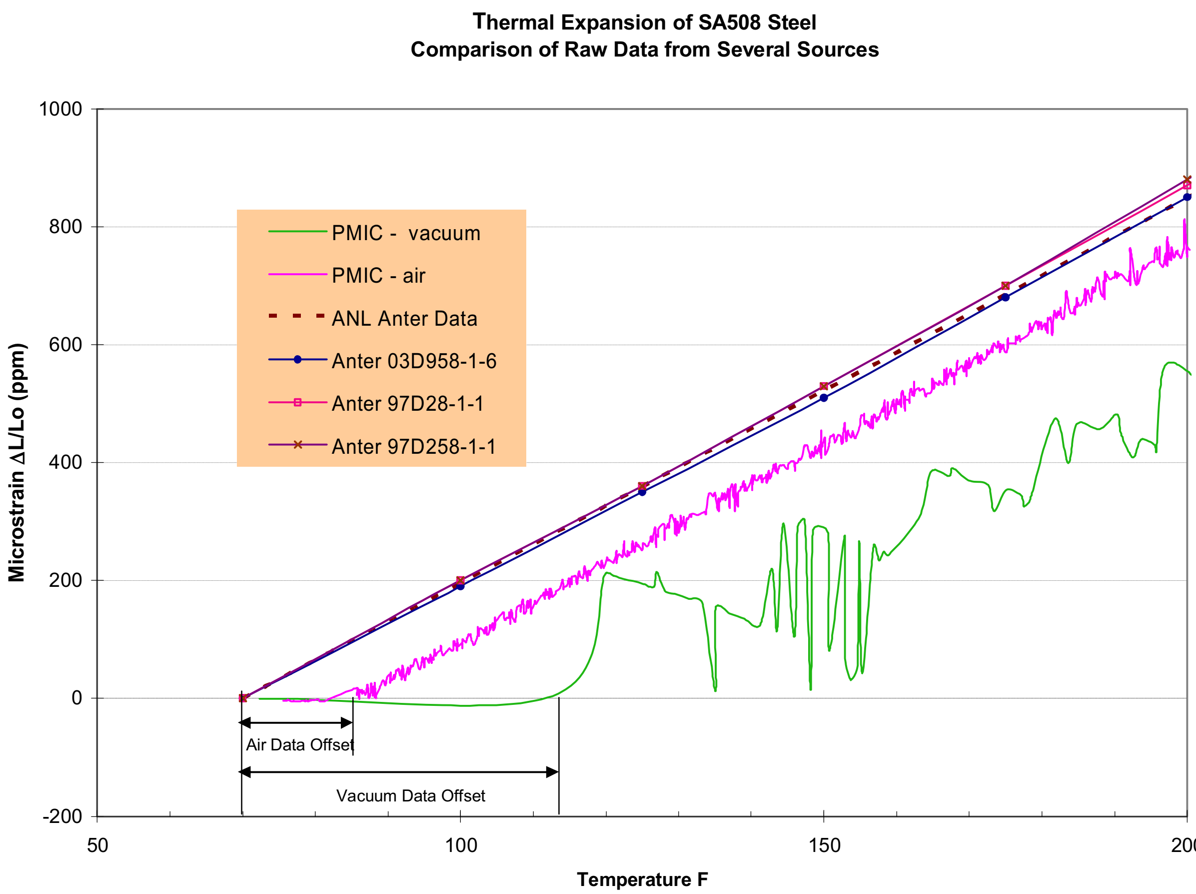

Figure A-2 – Expanded View of Low Temperature End of Figure A-1

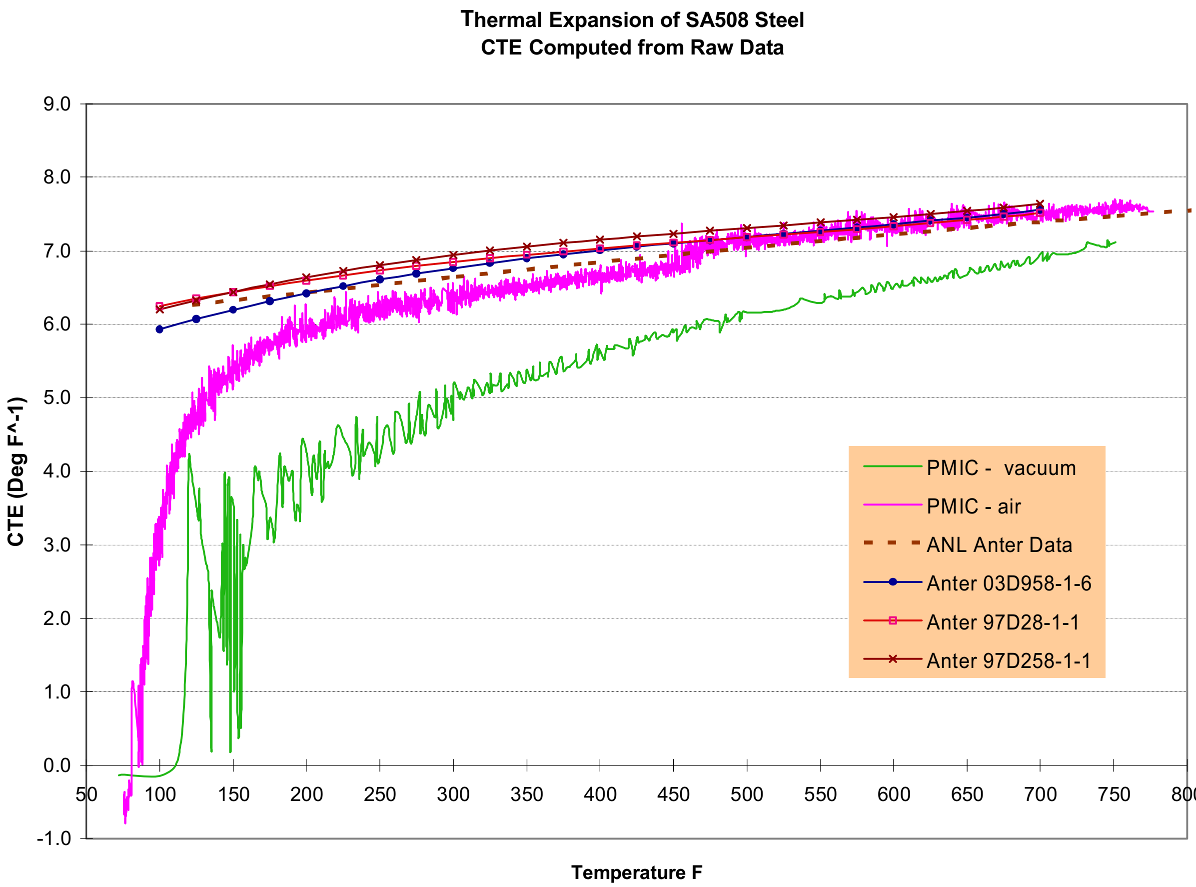

Figure A-3 – CTE Computed from Test Data of Figure A-1