NUCLEAR ENERGY INSTITUTE

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September 12, 2008

Mr. Joseph G. Giitter
Director, Division of Operating Reactor Licensing
U.S. Nuclear Regulatory Commission
Mail Stop E2C52
Washington, DC 20555

Subject: H*/B* Expert Panel Technical Evaluation - Re-assessment of Coefficient of Thermal Expansion Data for SA-508 Steel and Alloy 600.

Project Number: 689

Dear Mr. Giitter:

Industry representatives are currently working towards resolving the NRC comments on the H*/B* alternate repair criteria. The purpose of this letter is to provide statistical evaluations of the coefficient of thermal expansion (CTE) data for SA-508 Grade 2 and Alloy-600, including the new laboratory data, which results in a recommended statistical distribution of the data.

The ASME B&PV Code (Section II) 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%. However, the meaning of this uncertainty range is not defined in statistical terms. Furthermore, recent testing of the coefficient of thermal expansion (CTE) of a low alloy steel forging (SA-508 Grade 2) and of Alloy-600 by two independent laboratories have reported data that lie outside of the ±10% range for SA-508 Grade 2.

Enclosure 1 provides a statistical evaluation of CTE data for SA-508 Grade 2 and Alloy 600 material, including reassessed laboratory data, which results in a recommended statistical distribution of the data.

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Enclosure 2 provides new CTE data for A-508 and A-600 materials recently tested at ANTER laboratory as part of the Westinghouse H* program review. These results are superimposed on CTE data provided in Enclosure 1. Note that the March 28th letter report does not include the new ANTER data reported in the second enclosure; however we are in the process of updating the report to include the new data.

Overall results indicate that it is reasonable and conservative to continue to use the ASME curves as a baseline for H* analyses, since use of higher CTE for SA-508 and lower CTE for A-600 material tend to increase the gap between the steam generator tube and tube sheet. Details of the analyses are provided in the attached reports.

If you have any questions, please contact me at 202.739.8137; jhr@nei.org or Mike Melton at 202.739.8049;mam@nei.org.

Sincerely,

James H. Riley

Enclosures

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March 28, 2008
Report No. 0007080.401 (Draft)

H.O. Lagally
Westinghouse Electric Co, LLC
P.O. Box 158
Madison, PA 15663

Subject: **Evaluation of Uncertainties in ASME Code Coefficient of Thermal Expansion Properties for Low Alloy Steel and Alloy 600**

Introduction

The ASME B&PV Code (Section II) 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. Furthermore, recent testing of the coefficient of thermal expansion (CTE) of a low alloy steel forging (SA-508 Grade 2) and of Alloy-600 by two independent laboratories have reported data that lie outside of the ±10% range for SA-508 Grade 2.

The purpose of this report is to document a statistical evaluation of the CTE data for SA-508 Grade 2 and Alloy-600, including the new laboratory data as reassessed in [4], which results in a recommended statistical distribution of the data.

CTE Data Evaluated

Figures 1 and 2 present compilations of CTE data for the two materials from Reference [3], 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. The issue at hand is associated with the PMIC data for SA-508 Grade 2 presented in Figure 2, since these data lie outside of the ±10% error bands. A reassessment of these measurements was performed by Peter King, starting with the raw data, and is documented in Reference [4]. This reassessment concluded that there were anomalies in the data that lead to significant problems with the polynomial fit techniques used by PMIC, and that an alternate "weighted fit" technique seems to resolve that problem. Figure 3 is a replot of Figure 2, but with the original PMIC data replaced by the re-assessed "weighted-10" data from Reference [4]. The evaluation which follows utilizes the data presented in Figures 1 and 3 to establish statistical variability of the CTE data for the two materials.

Statistical Evaluation

The data in Figures 1 and 3 were evaluated using a standard probability plotting technique [5], which is a graphical technique for assessing whether or not a data set follows a given distribution such as the normal or Weibull. The CTE data were assessed in terms of their deviations (or residuals) from the current ASME curves for each material, which were assumed to represent a baseline. Data points were selected at approximately 50°F intervals in the temperature range of interest (70°F to 700°F) from the following data sets in Figures 1 and 3:

Data Sets included for Alloy-600:	Data Sets included for SA-508 Grade 2:
Specialty Metals Datasheet	MatWeb AISI 1020
Aero SM Handbook	ANL Anter
Mil Handbook 5	ANL PMIC (Weighted-10)
NSMH Values	
Miscellaneous Datasheets	
ANL Anter	
ANL PMIC	

The residuals between each individual data set and the applicable ASME curve were computed, sorted and plotted as a probability plot in which:

- Vertical axis: Ordered residual values
- Horizontal axis: Order statistic medians for the given distribution

Probability plots were developed in this manner for normal, log normal and Weibull distribution types for each material individually as well as for the two materials plotted together. Typical probability plots, generated from the combined data sets (i.e. residuals for both materials combined and plotted together) are illustrated in Figure 4 (normal) and Figure 5 (log normal). The correlation coefficient associated with the linear fits to the data in the probability plots is a measure of the goodness of the fit.

Review of the various data plots indicated that the combined data set plot with the log normal distribution (Figure 5) gave the best fit, but that the normal plot for the combined data (Figure 4) was almost as good. A normal distribution is recommended, however, because physical data such as CTE are expected to be normally distributed and because the relatively small improvement achieved with 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). Combining the data for the two materials was selected rather than analyzing each material individually, because only limited data sets are available for SA-508 Grade 2, and the numerical CTE values for the two materials are not hugely different. (Code CTE values are 7.5 x 10-6 in/in/°F for Alloy 600 and 7.1 x 10^{-6} in/in/°F for SA-508 Grade 2 at 400°F, which is approximately the midpoint of the temperature range of interest.)

The resulting normal distribution is illustrated, along the residual data in Figure 6. The standard deviation of the residuals is 0.233 x 10^{-6} in/in/°F, or 3.2% of the mean value for the two materials at the midpoint temperature (7.3 x 10^{-6} in/in/°F). It is seen from the plot that the normal distribution tends to over-predict variability of the data in the tails of the distribution, which would make it conservative for Monte Carlo analyses of steam generator tube pullout depths.

Discussion

The analyses presented in this report suggest a statistical distribution 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 Alloy 600 and SA-508 Grade 2, with a standard deviation of 3.2% of the Code values. This result suggests that the uncertainty of ±10% quoted in various ASME Code documents would correspond to approximately three standard deviations.

Use of such a distribution is considered conservative, because it tends to over-predict the variability of the data in the tails of the distribution. An alternative analysis by Jim Begley [6] computed a standard deviation of 2.4 % from 8 independent measurements (each data set considered to be an individual data point). It also opined that this variability is more a reflection of measurement uncertainty than heat to heat variation. Heat to heat variation is included in the 2.4% number but is considered to be a small contributor compared to lab to lab measurement uncertainty. Reference [6] thus suggests a normal distribution with a standard deviation of 1.2% for Monte Carlo analyses.

Very truly yours,

Peter C. Riccardella
Senior Associate

References:

1. ASME Boiler and Pressure Vessel Code, Section II. Part D, Subpart 2, 2004 Edition
2. "Thermophysical Properties of Ferrous Structural Alloys", R.A. Moen, Hanford Engineering Development Laboratory, HEDL-TME 78-47, EC-79b,h, April, 1978
3. Presentation: "Coefficient of Thermal Expansion and Other Material Property Uncertainties", Chris Hoffman, Westinghouse, Jan. 15, 2008
4. "Re-assessment of PMIC CTE Measurements", Peter King, B&W Canada, Feb. 29, 2008.
5. Chambers, John, William Cleveland, Beat Kleiner, and Paul Tukey, (1983), "Graphical Methods for Data Analysis", Wadsworth.
6. Email Correspondence, J. Begley (AREVA) to H. Lagally (Westinghouse), "Thermal Expansions Coefficients" dated 3/13/2008.

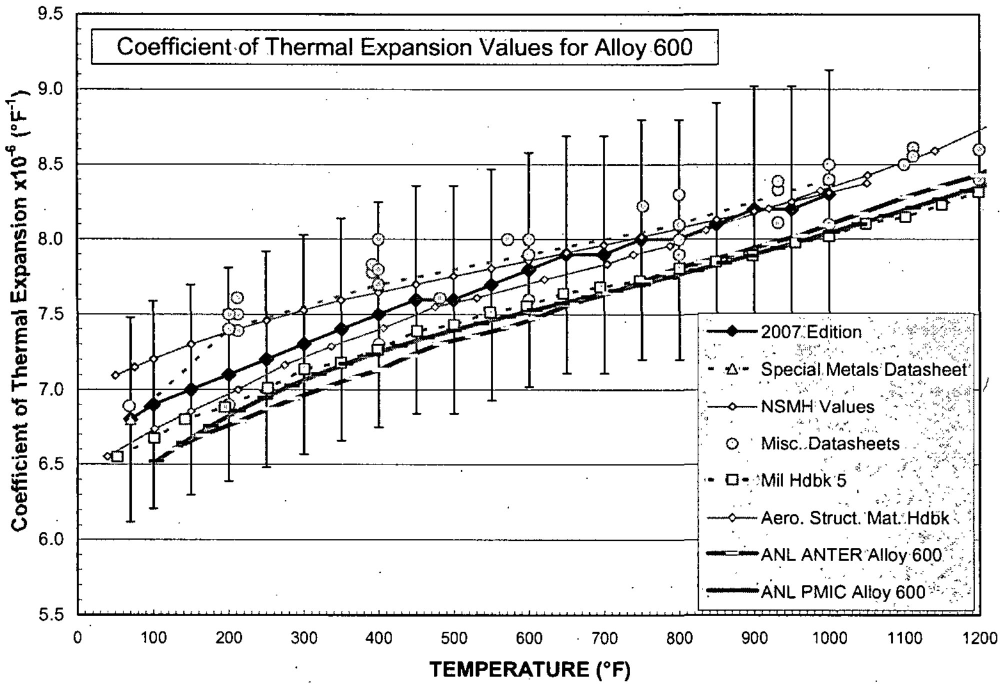


Figure 1 – CTE Data for Alloy 600 from Various Sources [3]

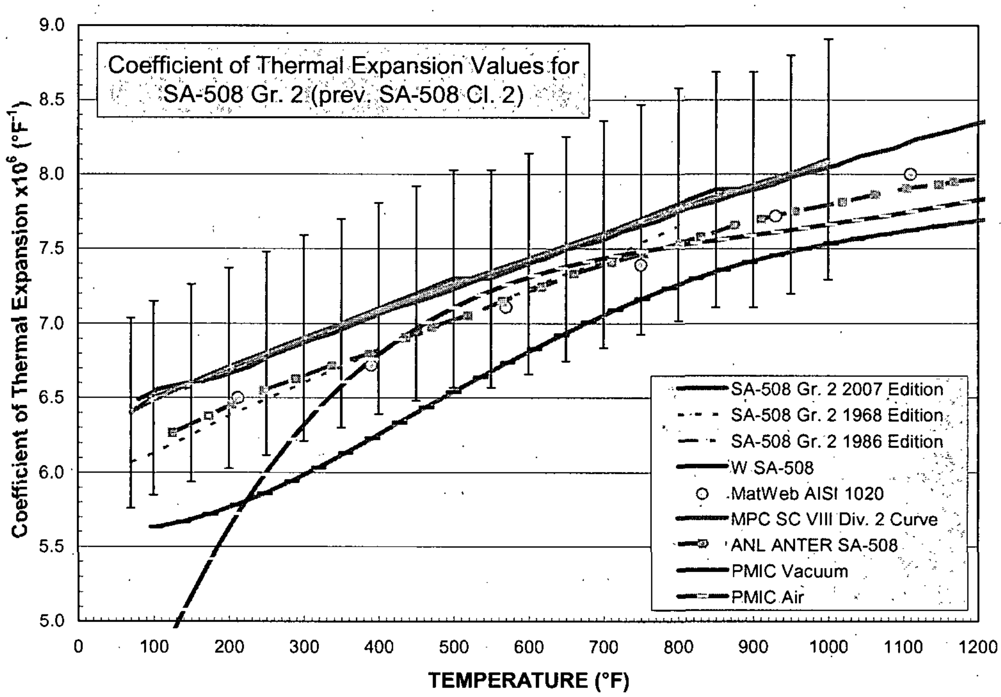


Figure 2 – CTE Data for SA-508 Grade 2 from Various Sources [3]

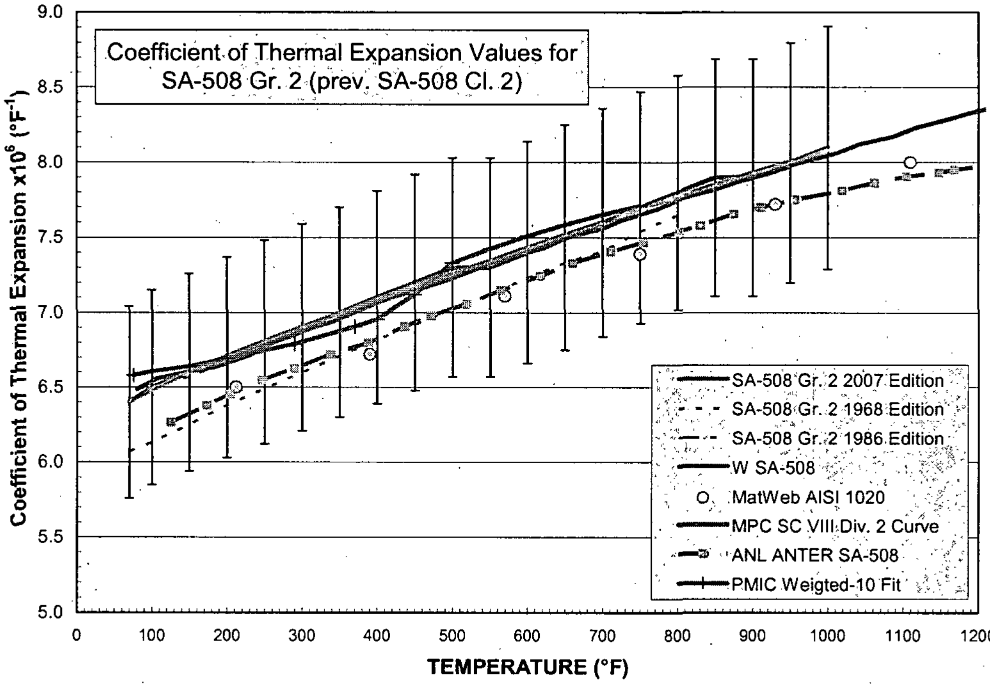


Figure 3 – CTE Data for SA-508 Grade 2 from Various Sources [3] with PMIC Data as Reassessed in [4]

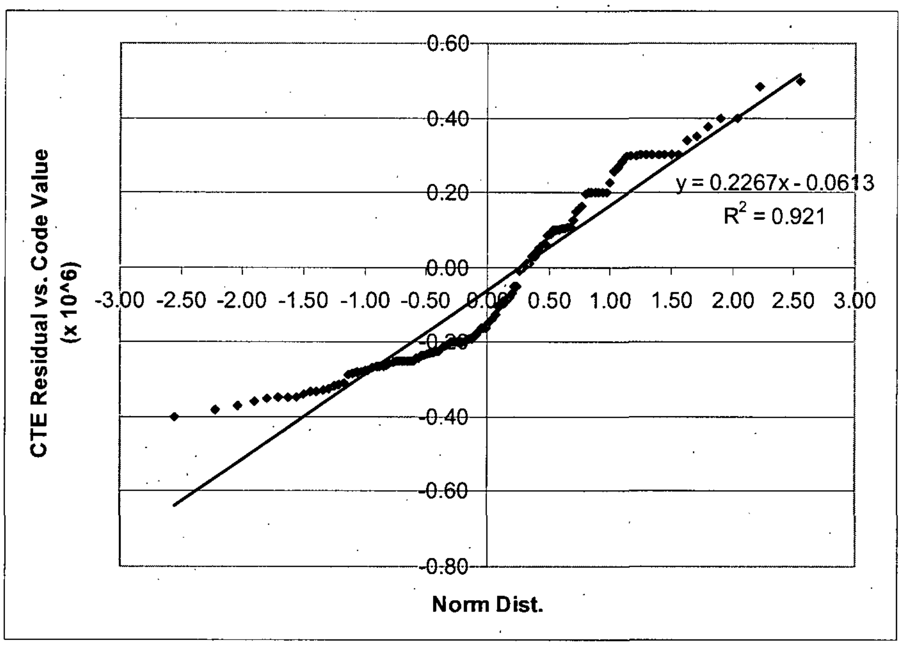


Figure 4 – Normal Probability Plot of CTE Residuals from ASME Code Values (Combined Plot for Both Materials)

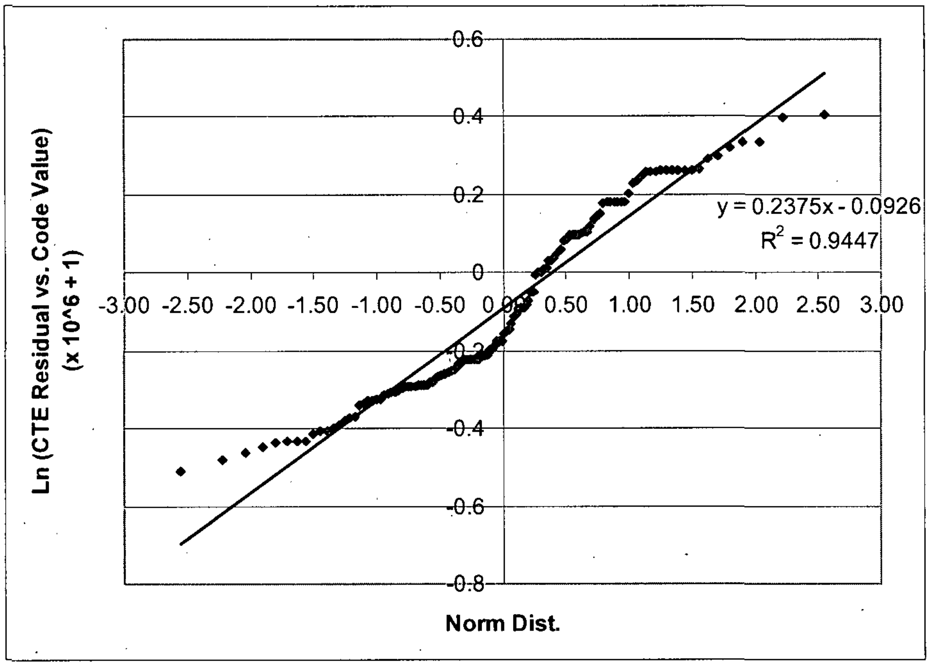


Figure 5 – Log Normal Probability Plot of CTE Residuals from ASME Code Values (Combined Plot for Both Materials)

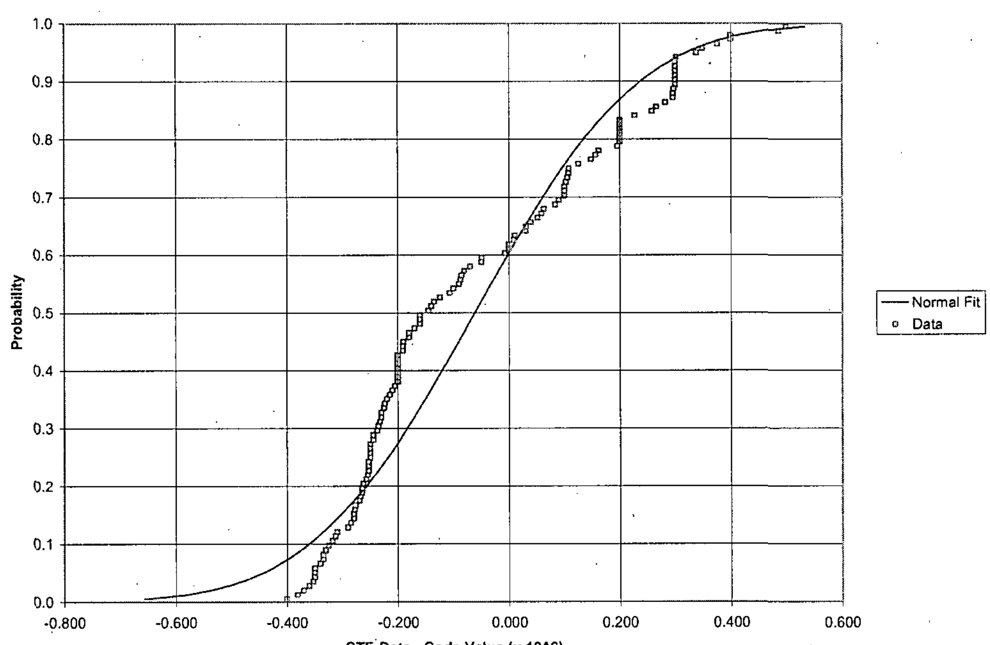


Figure 6 – Recommended Normal Distribution of CTE Data

Preliminary Transmittal of CTE Data
Peter C. Riccardella
Structural Integrity Associates, inc.
August 21, 2008

New Coefficient of Thermal Expansion (CTE) data for A-508 and A-600 materials recently tested at ANTER as part of the Westinghouse H* program are illustrated in Figures 1 and 2. The plots show the mean values of CTE for four heats of A-508 material (Figure 1) and nine heats of A-600 (Figure 2). These represent the means for ten samples tested per heat of A-508 and for three to four samples tested per heat of A-600 (total of 70 individual tests). The data are superimposed upon CTE data from other sources used in prior analyses (Ref. 1), as identified in the plot legends.

The new data are indicated by multi-colored symbols connected by heavy dashed lines in the plots, while the old data are shown as individual symbols with no connecting lines. Also shown in the plots are the current ASME Code curves applicable to the two materials (solid brown lines) and the overall means of all data sets, new and old (heavy black dashed lines). It can be seen from the plots that the new data sets are much more tightly grouped, and closer to the ASME curves, than the previous data sets. It is also observed that the overall mean curves of the data are very close to the ASME curves, except for some deviation in the A-508 curve at lower temperatures (<300°F) which is attributed to experimental error. The overall mean of the A-508 data lies below the Code curve and the overall mean of the A-600 curve lies on or above the ASME Code curve.(with the exception of one data point at 650°F). Thus it is reasonable and conservative to continue to use the ASME curves as a baseline for H* analyses, since use of higher CTE for A-508 and lower CTE for A-600 tend to increase the gap between tube and tube sheet. (The one low A-600 point at 650 F is beyond the temperature range of interest in the analyses.)

Statistical analyses were performed of the data sets illustrated in Figures 1 and 2 using previously reported methodology (Ref. 1). These result in preliminary recommendations for standard deviations of 1.75% for the A-508 material and 2.3% for the A-600.

Within-heat variability of the data for the two materials is illustrated in Figures 3 and 4. These are typical of the trends observed in all test heats. Note the trend of increased variability (on the order of 9% max to min) at lower temperatures, versus much lower variability (~2% max to min) at temperatures >300°F. This variability is attributed to testing uncertainty, since the measurements at lower temperatures require resolution of much smaller expansion values (on the order of 10 microns, using test equipment that is accurate to within ±1 micron). At temperatures greater than 300°F, the expansions are much greater. Thus the preliminary statistical analyses utilized heat means of the test data (i.e. Figs 1 and 2), and did not include the within-heat variability (Figs. 3 and 4), since the latter is considered to be due to testing uncertainty and not a true material variability. Additional testing is being performed to confirm this hypothesis. Additional testing is also underway of A-600 material that has been hydraulically expanded to evaluate the effect of strain hardening on the CTE property. The results of these additional tests will be addressed in the final analysis.

Reference:

1. Structural Integrity Letter Report No. 0007080.401, "Evaluation of Uncertainties in ASME Code Coefficient of Thermal Expansion Properties for Low Alloy Steel and Alloy 600", P. C. Riccardella to H. O. Lagally, March 28, 2008.

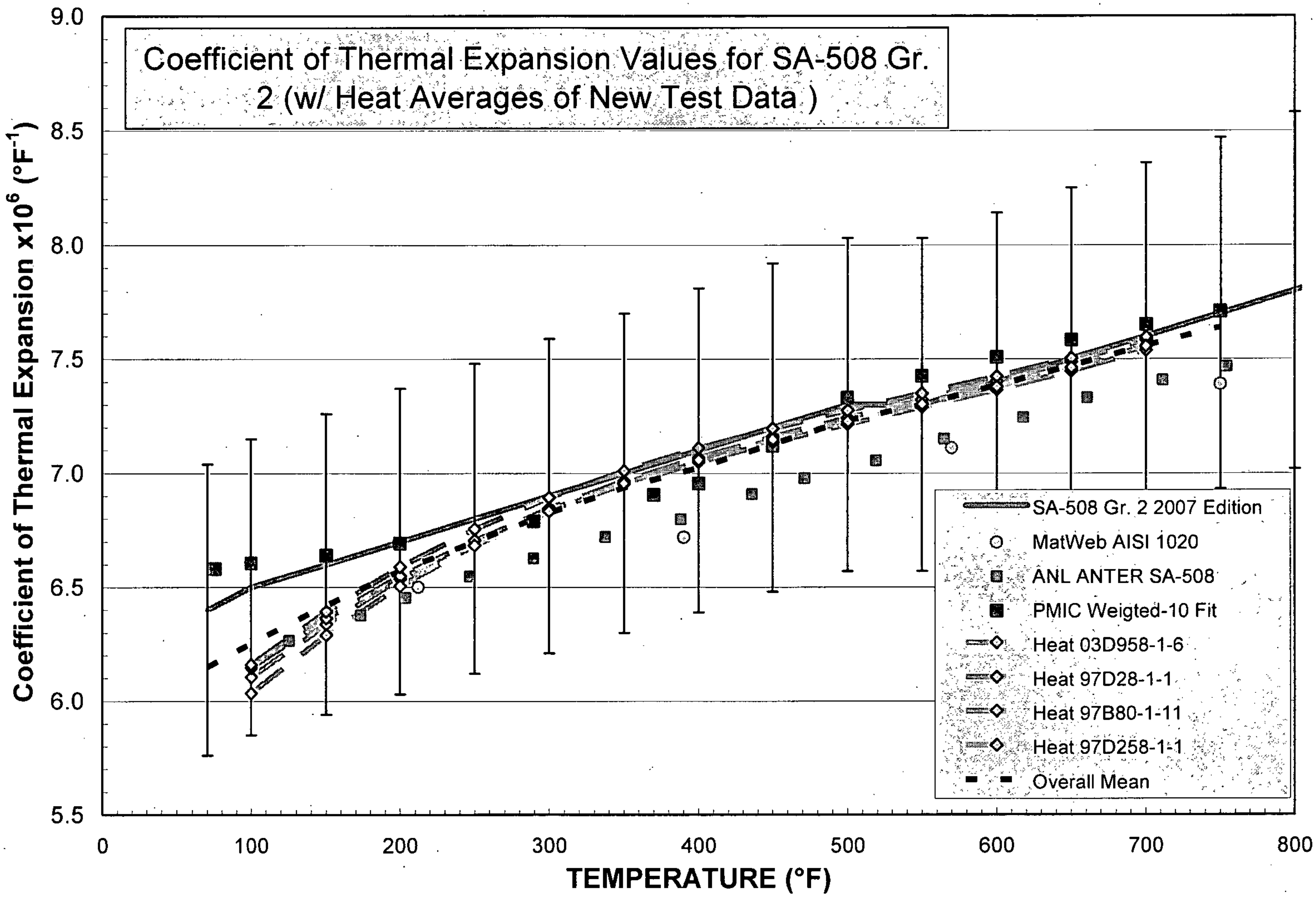

Coefficient of Thermal Expansion Values for SA-508 Gr. 2 (w/ Heat Averages of New Test Data)
Coefficient of Thermal Expansion x10^6 (°F^-1)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
0
100
200
300
400
500
600
700
800
TEMPERATURE (°F)
SA-508 Gr. 2 2007 Edition
MatWeb AISI 1020
ANL ANTER SA-508
PMIC Weigted-10 Fit
Heat 03D958-1-6
Heat 97D28-1-1
Heat 97B80-1-11
Heat 97D258-1-1
Overall Mean

Figure 1

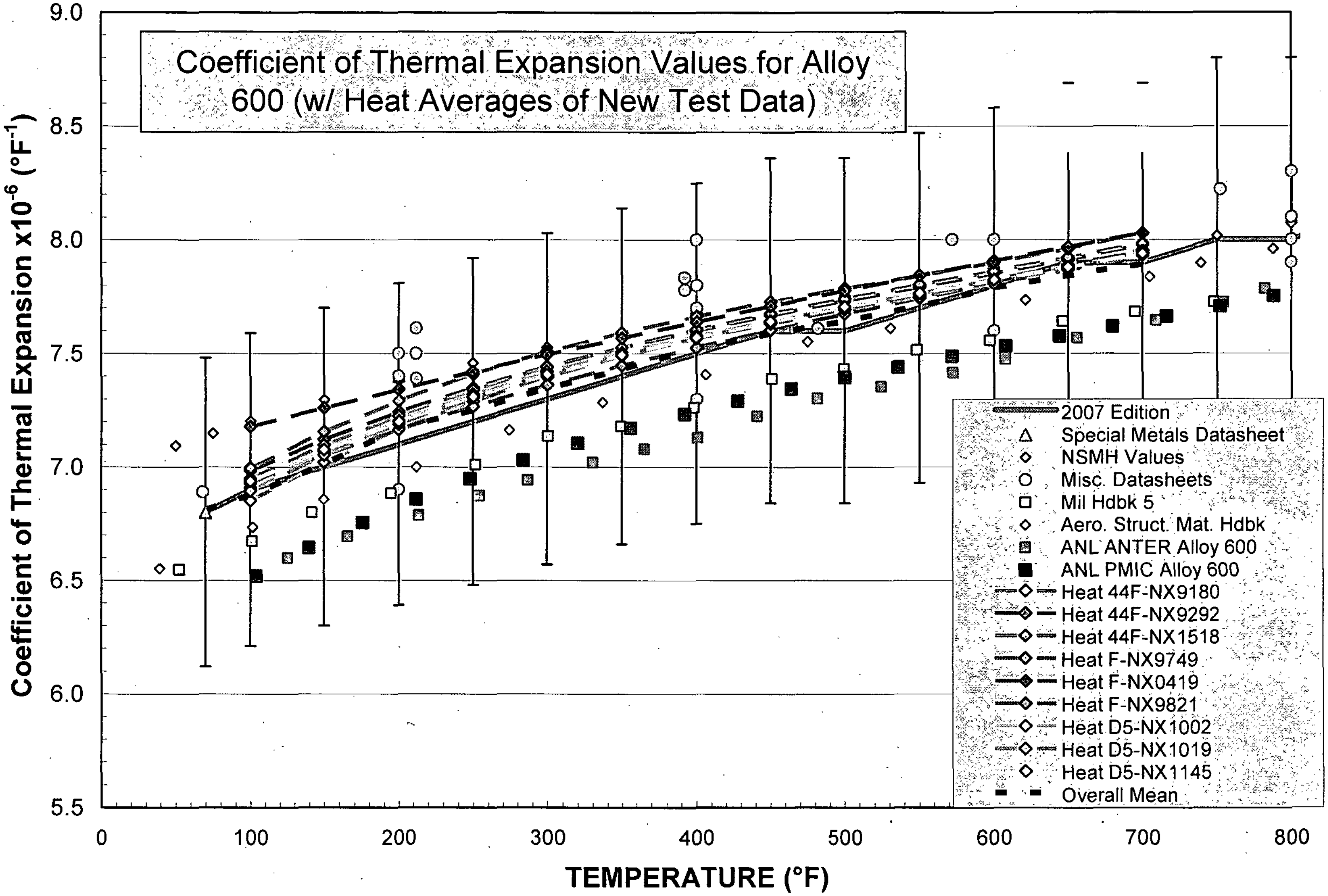

Coefficient of Thermal Expansion Values for Alloy 600 (w/ Heat Averages of New Test Data)
Coefficient of Thermal Expansion x10^-6 (°F^-1)
TEMPERATURE (°F)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
0
100
200
300
400
500
600
700
800
2007 Edition
Special Metals Datasheet
NSMH Values
Misc. Datasheets
Mil Hdbk 5
Aero. Struct. Mat. Hdbk
ANL ANTER Alloy 600
ANL PMIC Alloy 600
Heat 44F-NX9180
Heat 44F-NX9292
Heat 44F-NX1518
Heat F-NX9749
Heat F-NX0419
Heat F-NX9821
Heat D5-NX1002
Heat D5-NX1019
Heat D5-NX1145
Overall Mean

Figure 2

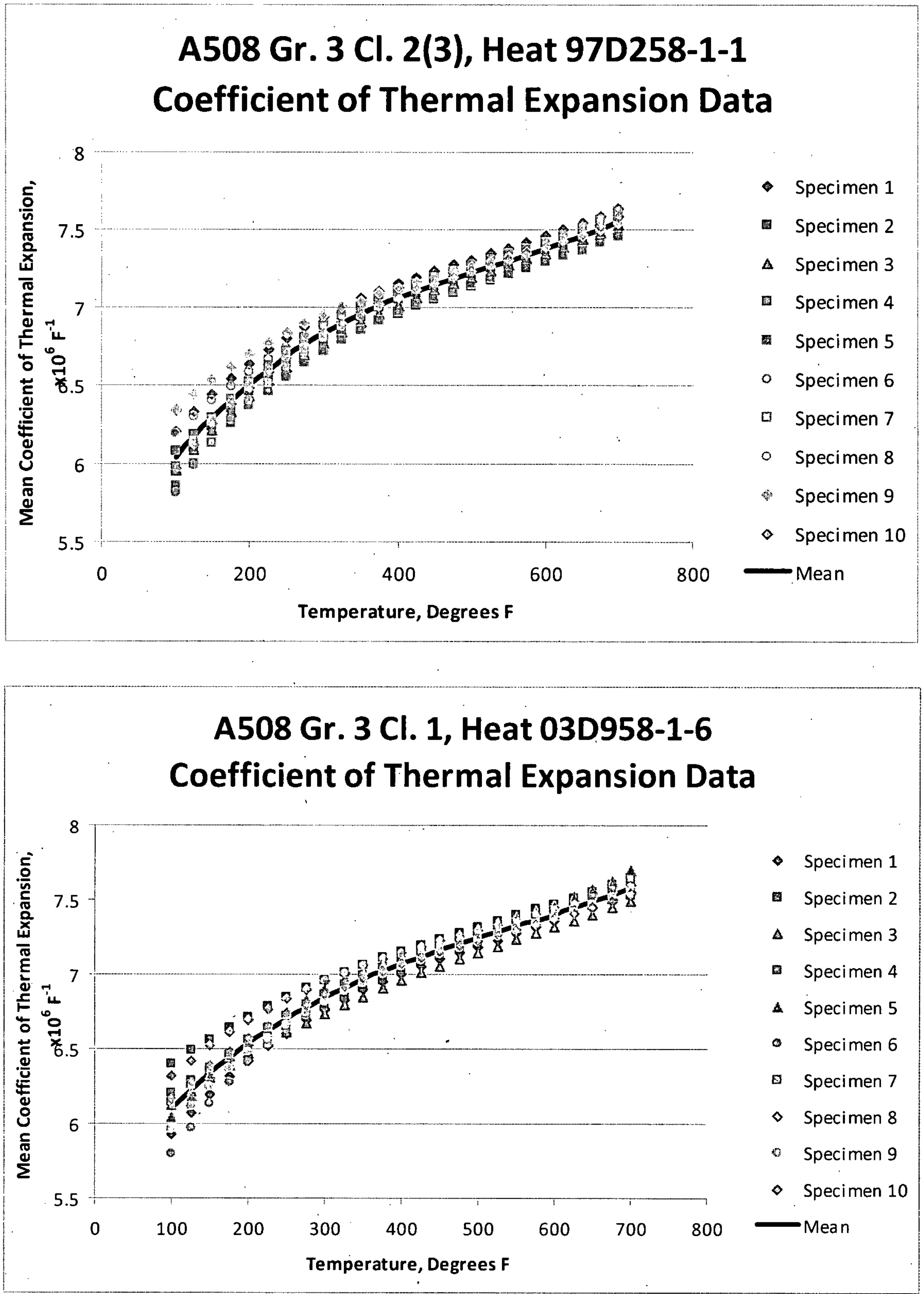
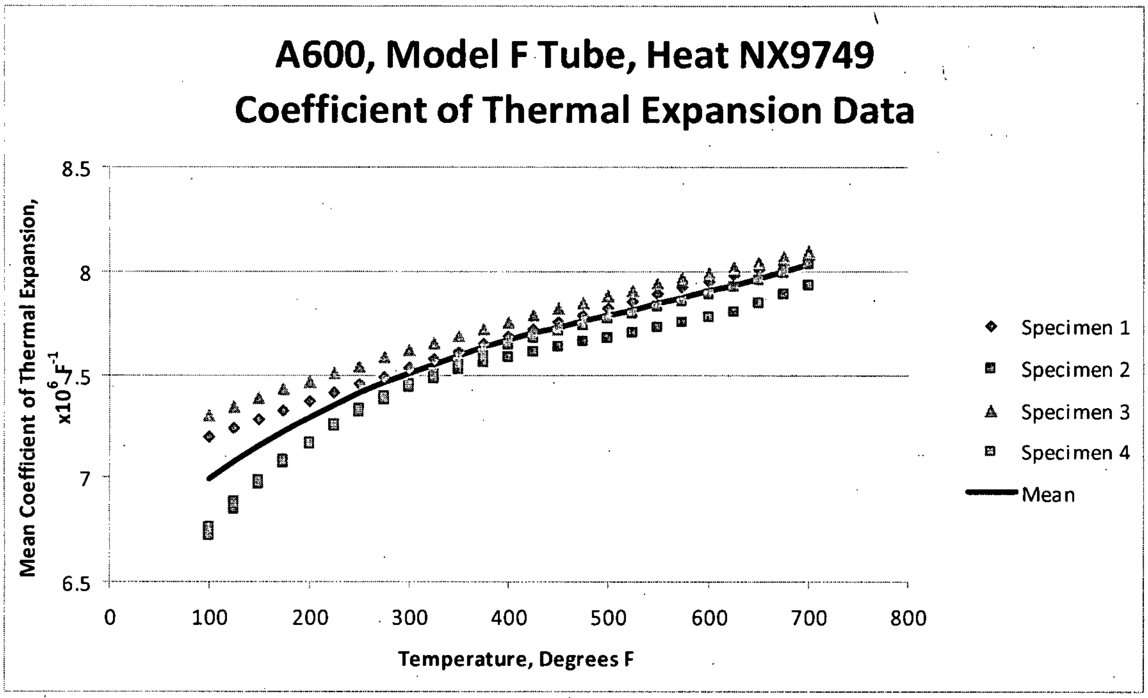

A508 Gr. 3 Cl. 2(3), Heat 97D258-1-1
Coefficient of Thermal Expansion Data
Mean Coefficient of Thermal Expansion, x10^6 F^-1
8
7.5
7
6.5
6
5.5
0
200
400
600
800
Temperature, Degrees F
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Specimen 5
Specimen 6
Specimen 7
Specimen 8
Specimen 9
Specimen 10
Mean
A508 Gr. 3 Cl. 1, Heat 03D958-1-6
Coefficient of Thermal Expansion Data
Mean Coefficient of Thermal Expansion, x10^6 F^-1
8
7.5
7
6.5
6
5.5
0
100
200
300
400
500
600
700
800
Temperature, Degrees F
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Specimen 5
Specimen 6
Specimen 7
Specimen 8
Specimen 9
Specimen 10
Mean

Figure 3


A600, Model F Tube, Heat NX9749
Coefficient of Thermal Expansion Data
Mean Coefficient of Thermal Expansion, x10^6 F^-1
8.5
8
7.5
7
6.5
0
100
200
300
400
500
600
700
800
Temperature, Degrees F
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Mean

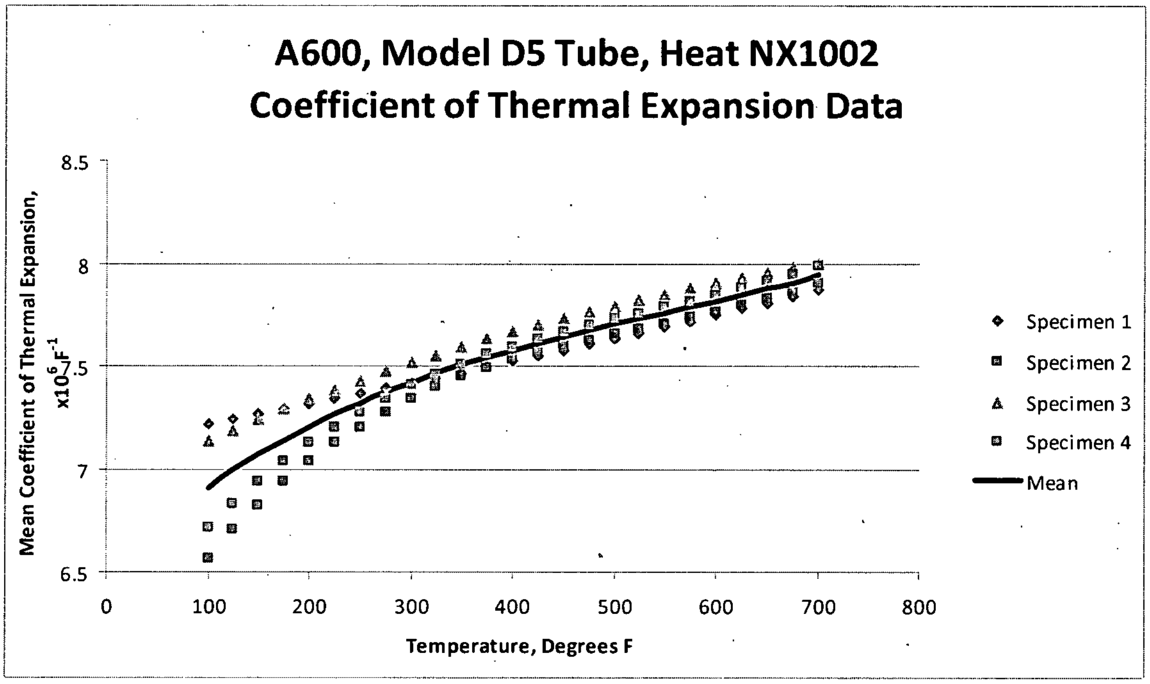

A600, Model D5 Tube, Heat NX1002
Coefficient of Thermal Expansion Data
Mean Coefficient of Thermal Expansion, x10^6 F^-1
8.5
8
7.5
7
6.5
0
100
200
300
400
500
600
700
800
Temperature, Degrees F
Specimen 1
Specimen 2
Specimen 3
Specimen 4
Mean

Figure 4