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STRUCTURAL INTEGRITY ASSOCIATES, INC

LETTER

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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,

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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.

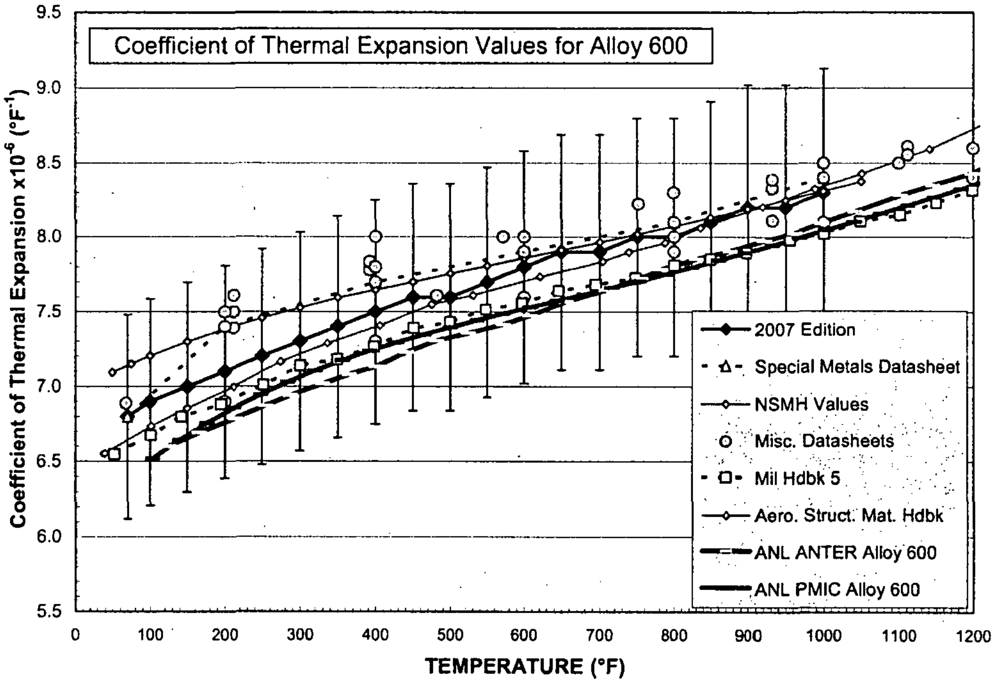

Figure 1 – CTE Data for Alloy 600 from Various Sources [3]

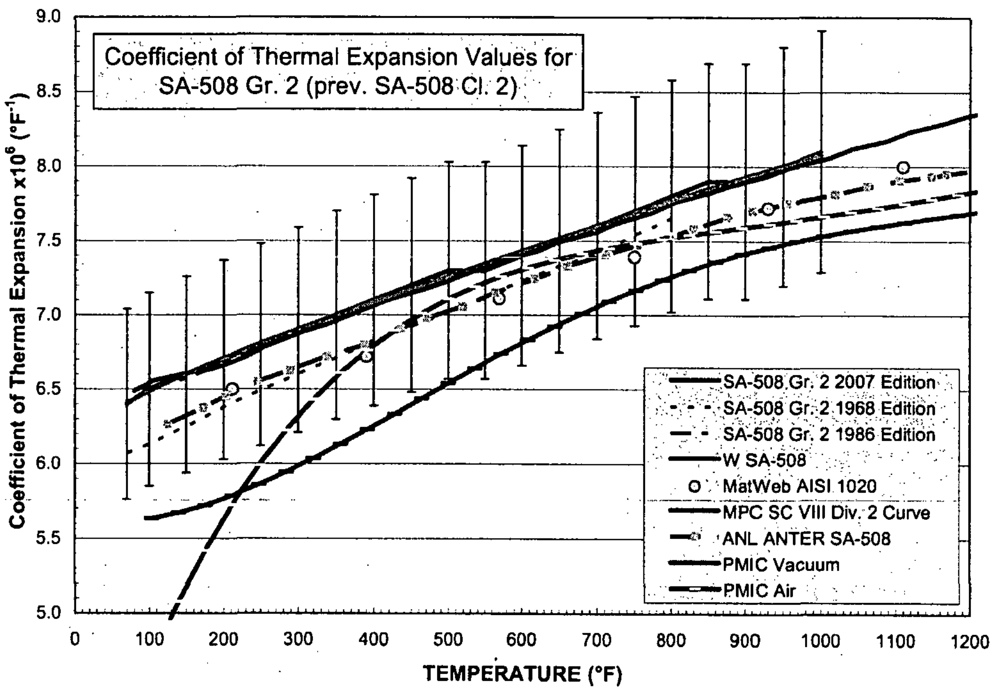

Figure 2 – CTE Data for SA-508 Grade 2 from Various Sources [3]

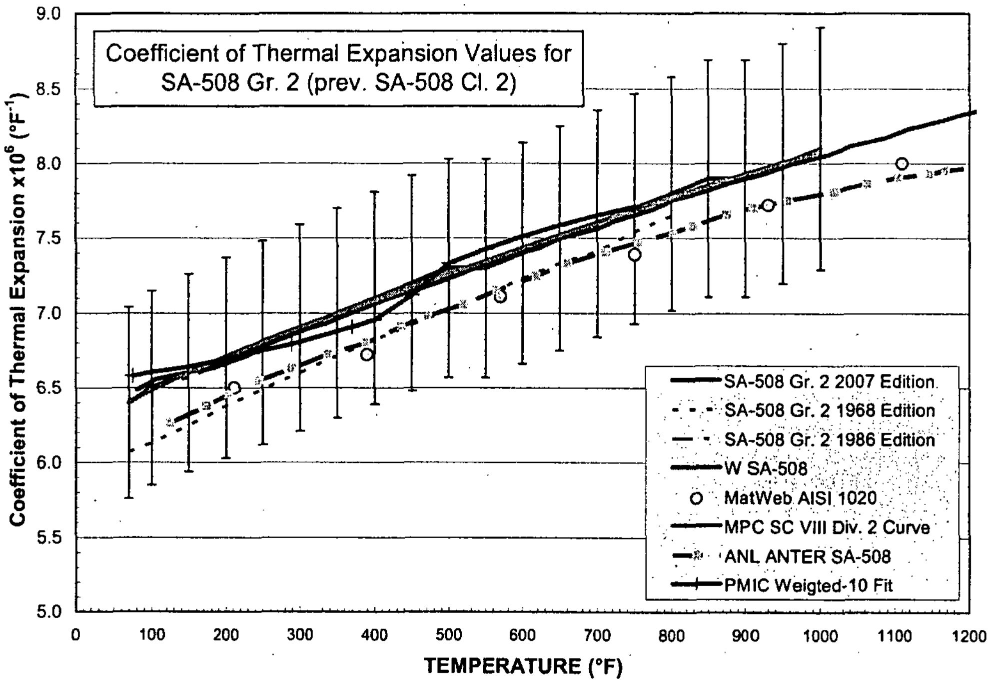

Figure 3 – CTE Data for SA-508 Grade 2 from Various Sources [3] with PMIC Data as Reassessed in [4]

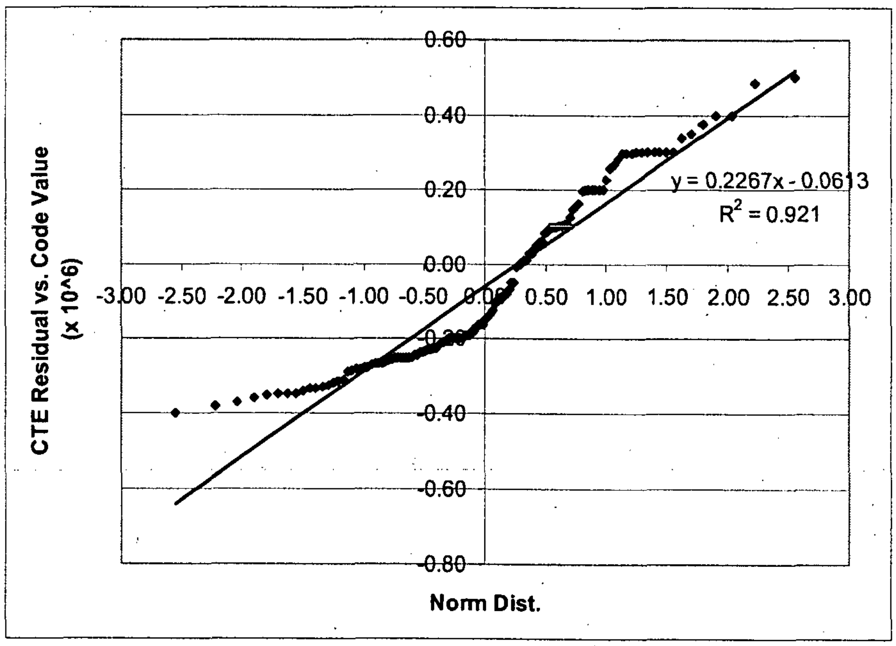

Figure 4 – Normal Probability Plot of CTE Residuals from ASME Code Values (Combined Plot for Both Materials)

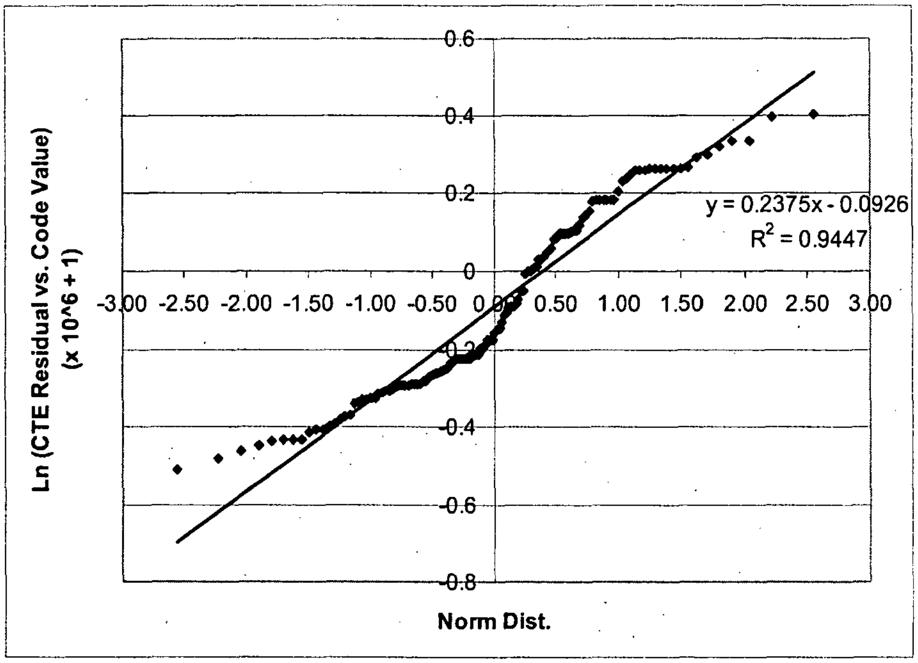

Figure 5 – Log Normal Probability Plot of CTE Residuals from ASME Code Values (Combined Plot for Both Materials)

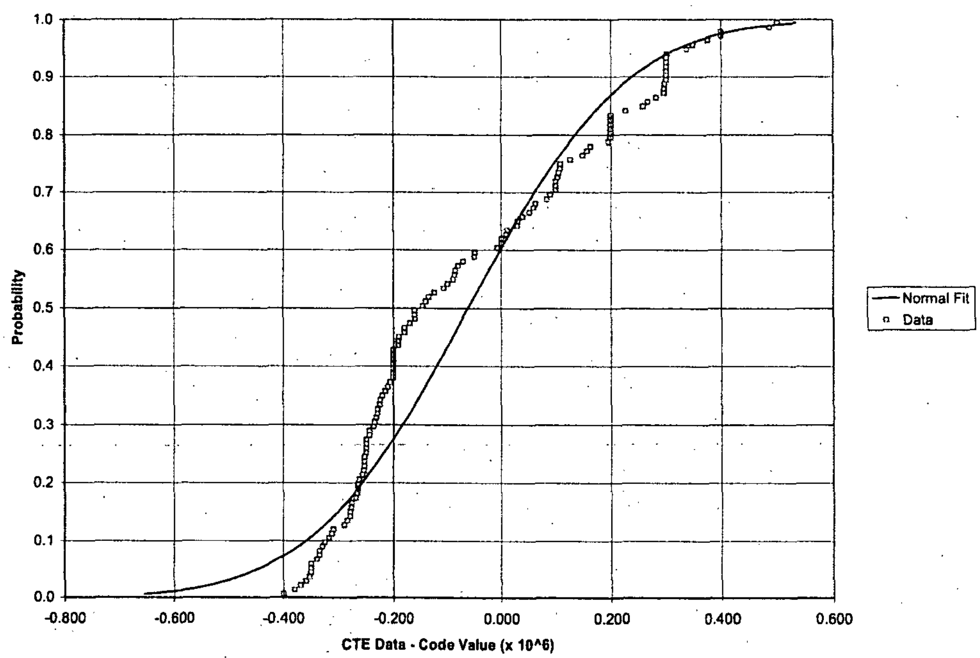

Figure 6 – Recommended Normal Distribution of CTE Data