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High Temperature Thermal and Structural Material Properties for Metals Used in LWR Vessels

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Abstract – *Because of the impact that melt relocation and vessel failure may have on subsequent progression and associated consequences of a Light Water Reactor (LWR) accident, it is important to accurately predict heating and relocation of materials within the reactor vessel, heat transfer to and from the reactor vessel, and the potential for failure of the vessel and structures within it. Accurate predictions of such phenomena require high temperature thermal and structural properties. However, a review of vessel and structural steel material properties used in severe accident analysis codes reveals that the required high temperature material properties are extrapolated with little, if any, data above 1000 K. To reduce uncertainties in predictions relying upon extrapolated high temperature data, Idaho National Laboratory (INL) obtained high data for two metals used in LWR vessels: SA 533 Grade B, Class 1 (SA533B1) low alloy steel, which is used to fabricate most US LWR reactor vessels; and Type 304 Stainless Steel SS304, which is used in LWR vessel piping, penetration tubes, and internal structures. This paper summarizes the new data, and compares it to existing data.*

I. INTRODUCTION

Melt relocation and vessel failure impact the subsequent progression and associated consequences of a Light Water Reactor (LWR) accident. Hence, it is important to accurately predict heating and relocation of materials within the reactor vessel and heat transfer to and from the vessel. Prior to INL efforts, a literature review[1-11] reveals that data are limited for two metals used in LWR vessels: SA 533 Grade B, Class 1 (SA533B1) low alloy steel, which is used to fabricate most US LWR reactor vessels; and Type 304 Stainless Steel SS304, which is used in LWR vessel piping, penetration tubes, and internal structures in vessels. Table 1 compares peak temperature data available prior to INL efforts with peak temperature data now available. As shown in this table, data were limited at temperatures above 1000 K for SA533B1 and above 1100 K for SS304 prior to INL efforts.

Severe accident analysis codes, such as SCDAP/RELAP5,[12] MELCOR,[13] and MAAP,[14] often extrapolate data to predict structural and thermal responses of the vessel and internal structures at higher temperatures. In the case of SA533B1, a ferrite-to-austenite phase transformation occurs at around 1000 K that can significantly alter its structural and thermal material properties.

TABLE I
Maximum test temperature in published data and INL tests

Material/Property	Maximum temperature in published data, K	Maximum temperature in INL tests, K
SA533B1		
Yield strength	922 [Reddy and Ayers, 1982]	1473
Ultimate strength	922 [Reddy and Ayers, 1982]	1473
Stress-strain curves	922 [Reddy and Ayers, 1982]	1473
Creep rupture data	922 [Reddy and Ayers, 1982]	1373
Creep strain data	922 [Reddy and Ayers, 1982]	1373
Thermal expansion	1000 [Rempe, 1993]	1573
Thermal diffusivity	1000 [Rempe, 1993]	1473
SS304		
Yield strength	923 [Smith 1969]	1366
Ultimate strength	1000 [Smith 1969]	1366
Stress-strain curves	977 [Dierks and Burke, 1974]	1366
Creep rupture data	1144 [Smith, 1969]	1350
Creep strain history	1089 [Swindeman, 1975]	1350
Thermal expansion	810 K [Touloukian, 1977]	1573
Thermal diffusivity	1273 K [Touloukian, 1973]	1473

To reduce unwanted uncertainties in predictions relying upon extrapolated data, the INL conducted high temperature tests for SA533B1 and SS304. Initial INL efforts to obtain structural data were completed over a decade ago. More recently, INL obtained high temperature thermal data. This paper highlights results from all of these tests and compares selected INL data to previously available data in the literature for these materials. More detailed information about INL tests completed to obtain this data may be found in the original documents reporting this data.[2, 15, 16, 17]

II. APPROACH

High temperature material property testing of SA533B1 and SS304 materials requires specialized equipment, unique fixturing and experienced staff. In addition to equipment capable of high temperatures, oxidation of test samples must be precluded. In these tests, temperatures were limited to prevent melting (@ 1789 K for SA533B1 and @ 1671 K for SS304). This section summarizes the specialized equipment and test fixturing used by INL to obtain high temperature structural and thermal data.

II.A. Tensile and Creep Data

High temperature tensile and creep data were conducted as part of the NRC-sponsored Lower Head Failure Program and the TMI-2 Vessel Investigation Project.[2, 15] Tensile and creep tests were conducted using American Society of Testing and Materials (ASTM) Standards.[18 through 20] Tensile tests were conducted in air. Creep tests were conducted in a chamber purged with argon gas that was installed around the test coupon to preclude sample oxidation (see Figure 1). The high ductility of sample material at test temperatures resulted in the use of large-ranging extensometers installed inside the chamber to measure the major portion of the time-dependent creep response. In the case of SA533B1, test coupons were fabricated from samples having either a meridional orientation with respect to the vessel lower head or a radial, or through-wall orientation, in the vessel plate material (Figure 1).

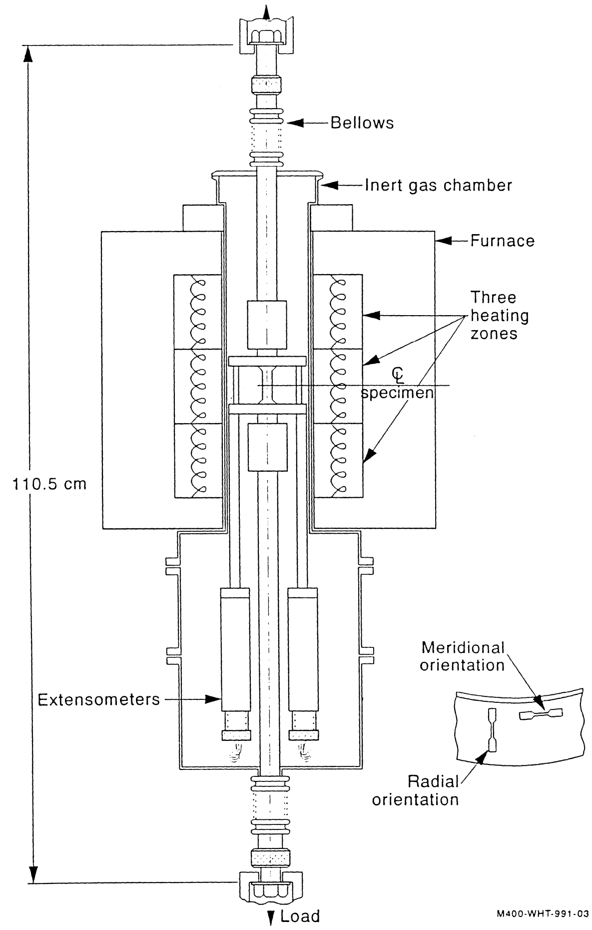

Fig. 1. Schematic diagram of the creep test setup.

In addition to sample orientation during fabrication, sensitivities to strain rate during testing were evaluated. In creep testing, material response is impacted by stress and temperature. A literature review revealed that published testing was often performed at much lower stresses than the INL tests. Typically, creep rupture times for published data are over 100 hours; whereas INL rupture times were typically obtained at around 10 hours, which is the timeframe of interest in severe accidents.

II.B. Thermal Diffusivity Data

Thermal diffusivity data were obtained using an Anter FL5000 system installed at INL's High Temperature Test Laboratory (HTTL) (see Figure 2). This system uniformly heats a small disk-shaped sample (typically, 12 mm in diameter and 2 to 4 mm thick) over its front face with a very short pulse of energy from a laser in a temperature-controlled furnace. The time-temperature history of the rear face of the sample is recorded through high-speed data acquisition from a solid-state optical sensor with very fast thermal response. Thermal diffusivity is determined from the time interval after the flash for the rear face to increase in temperature using the Clark and Taylor method.[21] Specific heat capacity and thermal conductivity data were estimated using comparative techniques with software provided by Anter and data from a reference sample with known thermal properties. INL tests included sensitivities to evaluate the impact of sample coating (graphite, boron nitride, and grit blasted), sample thickness (e.g., 2 to 4 mm), and voltage at which samples were tested (e.g., 1200 to 1500 V).

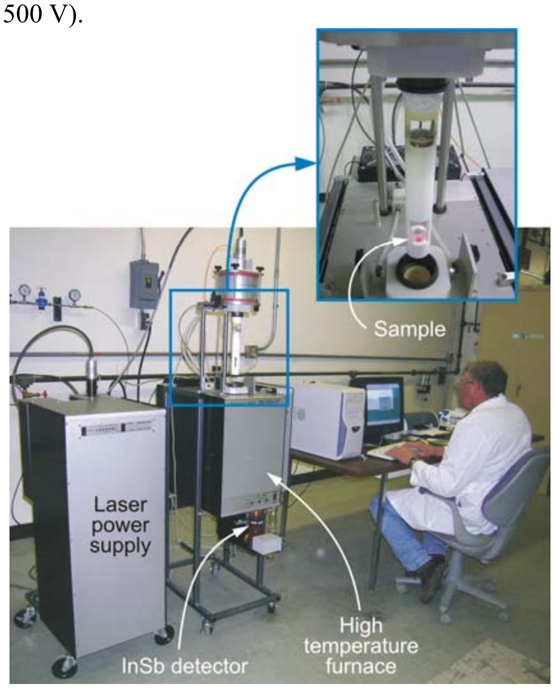

Fig. 2. Laser-flash Thermal Property Analyzer (Anter FL5000) installed at HTTL.

II.C. Thermal Expansion Data

Figure 3 shows the Netzsch DIL 402 ES dilatometer measurement system, also installed at INL's HTTL. The system consists of the dilatometer that contains the Linear Variable Differential Transformer (LVDT), the sample holder, and the furnace; the Thermal Analysis System Controller (TASC) 414/4 that links the dilatometer hardware to the measurement software; the furnace power source; the coolant system that keeps the LVDT at a constant temperature of 298 K; the vacuum pump (for evacuating oxidizing gases); and the Central Processing Unit (CPU) for recording and processing data. Samples were tested in two cycles, one up to 973 K and one up to 1473 K to verify that the initial heating doesn't impact thermal expansion data.

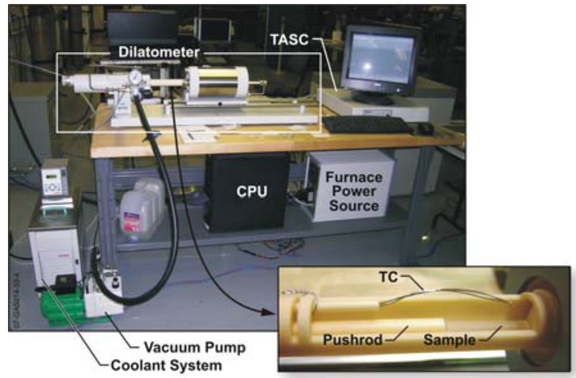

Fig. 3. Dilatometer measurement system installed at HTTL

III. SA533B1 DATA

As noted in Section 1, LWR vessels are manufactured from SA533B1, which undergoes a ferrite-to-austenite phase transformation at around 1000 K. Selected data reported in this section show that some material properties experience significant changes at this temperature.

III.A. Tensile and Creep Data

Figure 4 compares higher temperature INL ultimate strength data with previously published data.[3] The newer INL ultimate strength data show excellent agreement with data obtained at lower temperature.
Figure 4 compares higher temperature INL ultimate strength data with previously published data.[3] The newer INL ultimate strength data show excellent agreement with data obtained at lower temperature.

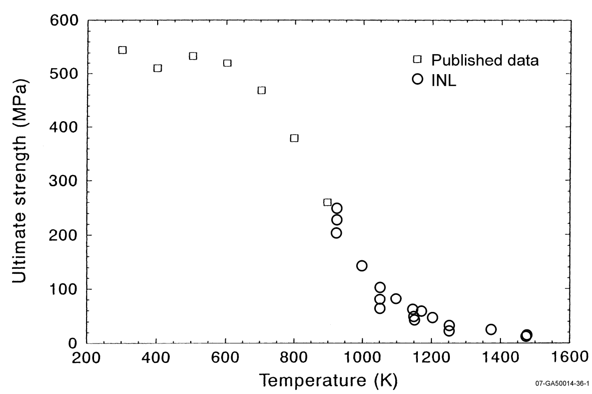

Fig. 4. Comparison of INL and published SA533B1 ultimate strength data.

A total of 13 creep tests were performed by INL with temperatures ranging from 900 to 1373 K and times to rupture ranging from 2 minutes to 264 hours. Time-dependent creep measurements were recorded as well as the times to rupture for the material. Figure 5 summarizes results, plotting the times to rupture for the applied stresses and corresponding temperatures.

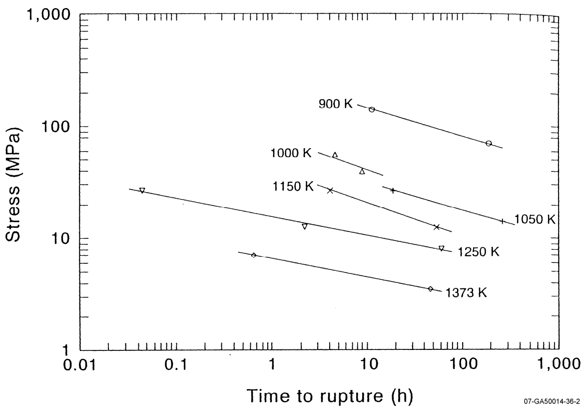

Fig. 5. Creep rupture stress versus time to rupture for SA533B1.

III.B. Thermal Diffusivity Data

Thermal diffusivity data for SA533B1 samples tested at INL are plotted in Figure 6. The SA533B1 data were obtained from testing 9 samples with thicknesses varying from 2 to 4 mm, laser powers varying from 1000 to 1500 V, and various types of coatings (graphite, boron nitride, and grit blasted). Data suggest that variations in test parameters did not significantly affect test data. However, there is more scatter in higher temperature SA533B1 data. In particular, a change in the behavior of the SA533B1 diffusivity occurs at temperature above 1000 K, which is the temperature where this material starts to experience a transformation (from ferritic to austenitic steel).

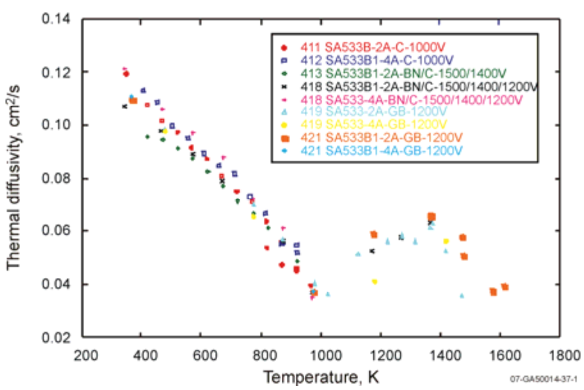

Fig. 6. SA533B1 thermal diffusivity data.

Figure 7 compares a curve fit for the new, higher temperature SA533B1 data with a thermal diffusivity curve based on published data.[2]. The new SA533B1 curve fit is similar (but somewhat lower) than published data.

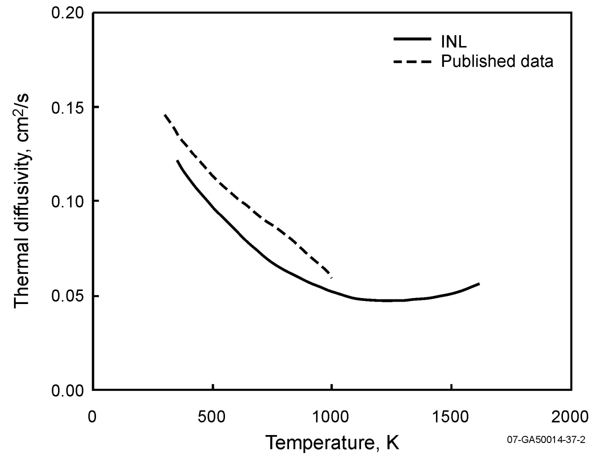

Fig. 7. Comparison of INL and published SA533B1 thermal diffusivity data.

III.C. Thermal Expansion Data

Figure 8 shows data collected to 1473 K for three carbon steel samples (CS-A, CS-B, and CS-C). The sudden drop occurs in thermal expansion at the 1000 K transition temperature for this material. Although all of the tests were conducted in argon, it is suspected that slight differences in the data may be due to different levels of oxidation or decarburization that may have occurred in the samples during these initial tests. The sensitivity of the dilatometer to sources of vibration may have also caused some error. Nevertheless, the data were found to agree with 10% in the transition region and 3% for higher temperature data.

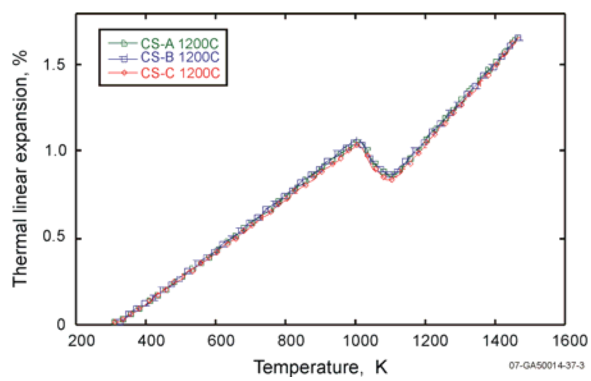

Fig. 8. Thermal expansion data for three samples of SA533B1.

Figure 9 compares the newly obtained carbon steel data, based on the average values shown in Figure 8, with values published in the literature.[2] As noted in Section 2, prior data had only been obtained below the transition temperature of this material. Hence, existing data did not consider the dip that was measured at temperatures above the transition temperature. As shown in Figure 9, the new data are significantly smaller in magnitude than values that one would obtain from extrapolating previously available data that do not consider the transition temperature.

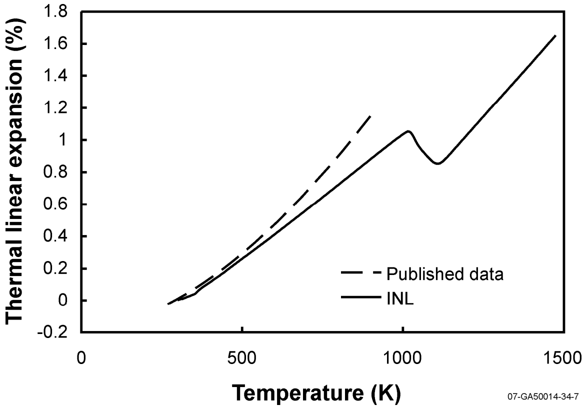

Fig. 9. Comparison of INL and published SA533B1 thermal expansion data.

IV. SS304 DATA

Stainless steels are iron based alloys containing at least 10.5% chromium. They achieve their stainless characteristics through the formation of an invisible and adherent chromium rich oxide film. Alloy 304 is a general purpose austenitic stainless steel with a face centered cubic structure. It is essentially non-magnetic in the annealed condition and can only be hardened by cold working. Type 304 Stainless Steel (SS304), which is used in LWR vessel piping, penetration tubes, and internal structures, does not undergo the phase transition observed in SA533B1 steel. However, as discussed in Section 2, limited amounts of data for temperatures above 1100 K were available in the literature prior to INL efforts.

IV.A. Tensile and Creep Data

Figure 10 compares higher temperature INL ultimate strength data with published values.[5,6,10,11] The newer INL data compare well with the published data obtained at lower temperatures.

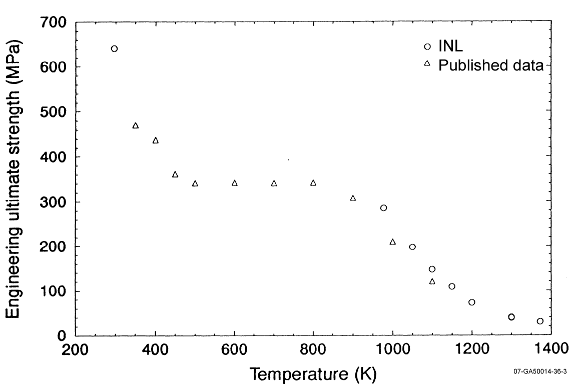

Fig. 10. Comparison of INL and published SS304 ultimate strength data.

SS304 creep data were obtained by INL for six tests run from 1089 to 1350 K. Stresses varied from approximately 9 to 85 MPa, and times to rupture ranged from 1 to 85.3 hours. These data and previously published data[4] are plotted in Figure 11. INL data at 1089 K fit reasonably well with the published data and are consistent with tests at different temperatures.

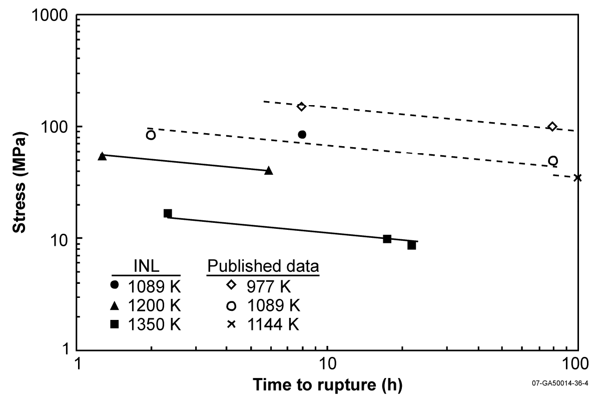

Fig. 11. Comparison of INL and published SS304 stress versus time to rupture data.

IV.B. Thermal Diffusivity Data

Thermal diffusivity data for stainless steel samples (SS304) are plotted in Figure 12. As indicated by the legend in this figure, SS304 data were obtained from testing 13 samples with thicknesses varying from 2 to 4 mm, laser powers varying from 1000 to 1500 V, and various types of sample coatings (graphite, boron nitride, and grit blasted). Data in this figure suggest that variations in test parameters did not produce any discernible trend in the test data.

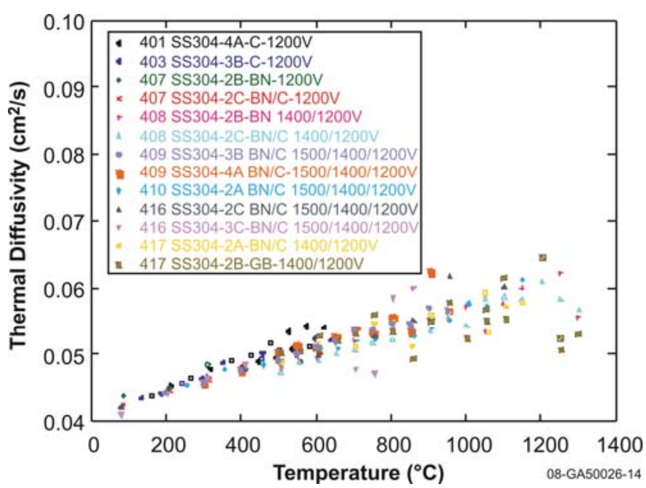

Fig. 12. SS304 thermal diffusivity data.

Figure 13 compares a curve fit for the new SS304 data with a curve based on data published in Touloukian.[8] As noted in Section 2, Touloukian values for stainless steel are extrapolated above 1273 K. As shown in Figure 3, the new SS304 data are higher than values published by Touloukian.

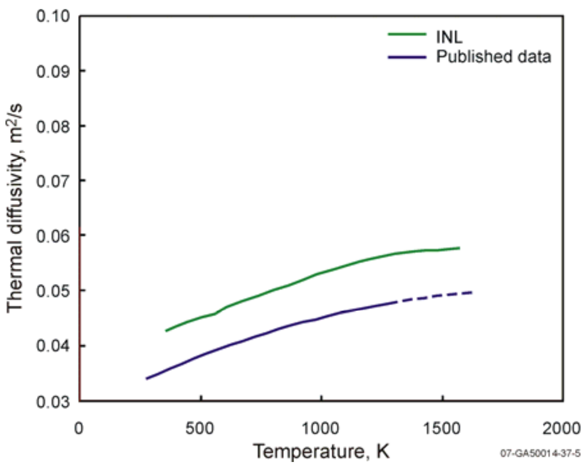

Fig. 13. Comparison of INL and published SS304 thermal diffusivity data.

IV.C. Thermal Expansion Data

Figure 14 shows data collected to 1473 K for two stainless steel samples (SS-A and SS-B). The data for the two samples are very consistent, showing about 1% variation for temperatures above 573 K.

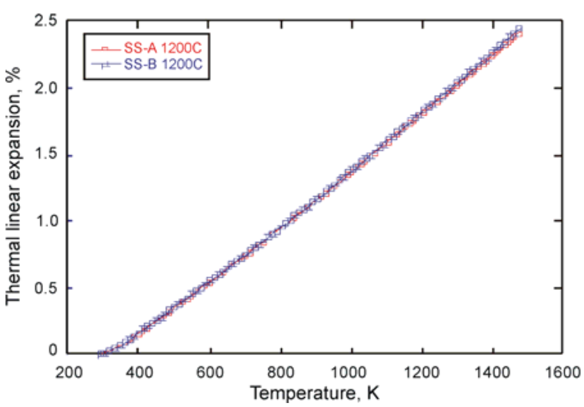

Fig. 14. Thermal expansion data for two SS304 samples.

Figure 15 compares a curve based on average values from Figure 14 with published values.[9] . As shown in this figure, the new data are consistent with previously published values.

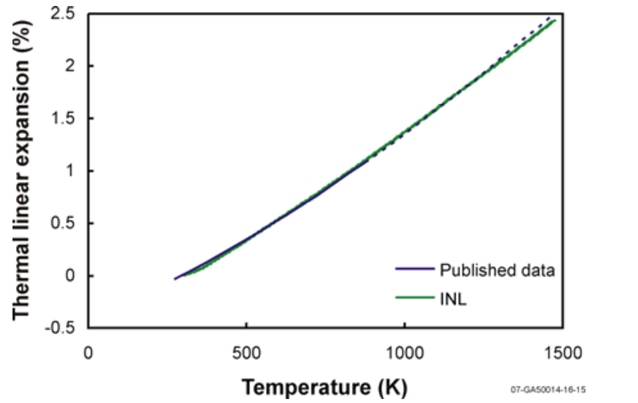

Fig. 15. Comparison of INL and published data for SS304 thermal expansion.

V. SUMMARY AND RECOMMENDATIONS

To reduce uncertainties in predictions relying upon extrapolated high temperature data, INL obtained new data for two metals used in LWR vessels: SA 533 Grade B, Class 1 (SA533B1) low alloy steel, which is used to fabricate most US LWR reactor vessels; and Type 304 Stainless Steel (SS304), which is used in LWR vessel piping, penetration tubes, and internal structures.

Evaluation of tensile and creep data for SA533B1 indicate that, while the phase transformation at 1000 K reduces the material's yield strength, the plots of stress versus time to rupture indicate only a moderate sensitivity to phase transformation. The 304 stainless steel tensile data show good consistency with published data extrapolated to 1366 K.

Laser-flash thermal diffusivity techniques were applied to obtain thermal diffusivity data up to 1673 K for these metals. Low temperature results (less than 1273 K) are similar to data published in the literature (at least for those materials where data were available in the literature). High temperature diffusivity data obtained for stainless steel differ by as much as 25% from values reported in the literature (although it should be noted that literature values were extrapolated for temperatures above 1273 K) and no values were available for SA533B1 above its transition temperature.

Pushrod dilatometry techniques were employed to obtain thermal expansion data obtained for these metals. Resulting data were found, in general, to be consistent with published values for low temperatures (e.g., below 673 K). For higher temperatures, new expansion data varied by over 20% from published extrapolated data. Note that in the case of SA533B1, the error introduced by extrapolating existing data to values above its transition temperature may introduce even larger errors (exceeding factors of two) because prior data was only obtained below this material's transition temperature.

In summary, the new high temperature structural and thermal property data were often consistent with lower temperature values published in the literature. However, in some cases, higher temperature values differed significantly from extrapolations of lower temperature published values. In the case of SA533B1, the transition from ferritic to austenitic steel at 1000 K made it impossible to extrapolate some properties at higher temperatures. In such cases, more testing is needed to reduce uncertainties. In addition, data for these materials are needed for other properties, such as specific heat capacity.

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