INL/EXT-17-43823
Revision 0

AGC-3 Specimen Post-Irradiation Examination Data Package Report

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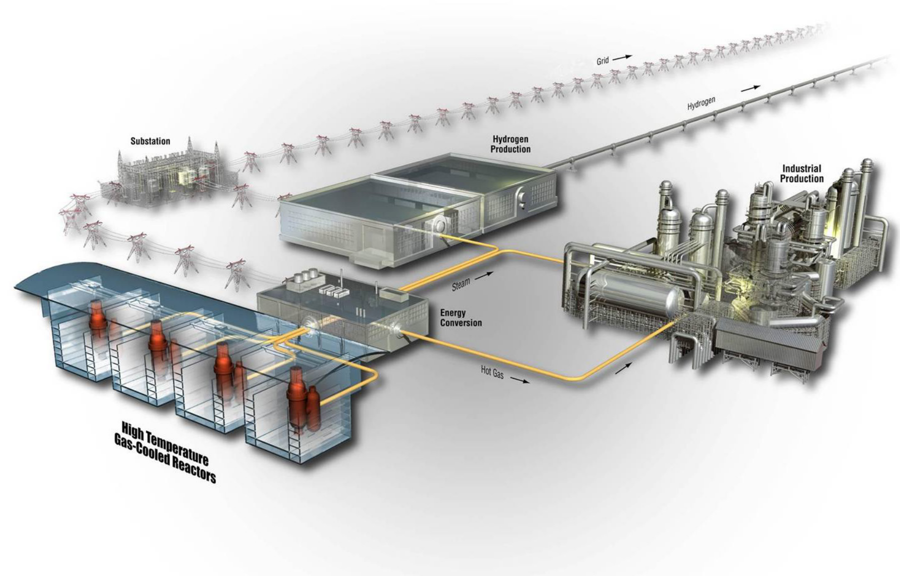

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

INL ART TDO Program

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SUMMARY

This report documents results of the post-irradiation examination material property testing from the third advanced graphite creep (AGC), AGC-3, capsule specimens. This is the third of a series of six irradiation test trains planned as part of the AGC experiment to fully characterize the neutron irradiation effects and radiation creep behavior of current nuclear graphite grades to moderate dose levels (≤7 dpa). The AGC-3 capsule was irradiated in the Idaho National Laboratory Advanced Test Reactor at a nominal temperature of 820°C and to a peak dose of 3.7 dpa. Half of the AGC-3 specimens were subjected to compressive stresses to induce irradiation creep. All post-irradiation testing and measurement results are reported with the exception of the irradiation mechanical strength testing, which is the last destructive testing stage of the irradiation testing program. The data reported includes specimen dimensions for both stressed and unstressed specimens to establish the irradiation creep rates, mass and dimensional data necessary to derive density, elastic constants (Young's modulus, shear modulus, and Poisson's ratio) from ultrasonic time of flight velocity measurements, Young's modulus from the fundamental frequency of vibration, electrical resistivity, and thermal diffusivity and thermal expansion data from 100 to 650°C.

An abridged statistical analysis was performed on the irradiated data and a limited comparison between pre- and post-irradiation properties is presented to ensure that any property measurements exhibiting values significantly higher or lower than the average were not a measurement error. A more complete evaluation of trends in the material property changes, as well as irradiation-induced creep due to the irradiation environment and applied load on the specimens, will be discussed later in AGC-3 post-irradiation examination analysis reports.

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ABBREVIATIONS

AG	against-grain
AGC	advanced graphite creep
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
COV	coefficient of variance
CTE	coefficient of thermal expansion
HOPG	highly ordered pyrolitic graphite
HTR	high-temperature reactor
HTV	high temperature vessel
INL	Idaho National Laboratory
IQR	interquartile range
MSR	molten salt reactor
PB	pebble bed
PIE	post-irradiation examination
SGL	SIGRI GmbH Great Lakes
WG	with-grain

AGC-3 Specimen Post-Irradiation Examination Data Package Report

1. INTRODUCTION

The Advanced Reactor Technologies Graphite Research and Development Program is conducting an extensive graphite irradiation program to provide data to assist in licensing of a high-temperature reactor (HTR) design. In past applications, graphite has been used effectively as a structural and moderator material in both research and commercial high-temperature gas-cooled reactor designs.[1,2] Nuclear graphite H-451, used previously in the United States for nuclear reactor graphite components, is no longer available. New nuclear graphite grades have been developed and are considered suitable candidates for new HTR designs. To support the design and licensing of HTR core components within a commercial reactor, a complete properties database must be developed for these current grades of graphite. Quantitative data on in-service material performance is required for the physical, mechanical, and thermal properties of each graphite grade with a specific emphasis on data accounting for the life-limiting effects of irradiation creep. Further details on the research and development activities and associated rationale required to qualify nuclear-grade graphite for use within the HTR are documented in the graphite technology development plan.[3]

Based on experience with previous graphite core components, the phenomenon of irradiation-induced creep within the graphite has been shown to be a critical parameter in determining the total useful lifetime of graphite components. Irradiation-induced creep occurs under the simultaneous application of high temperatures, neutron irradiation, and applied stresses within the graphite components. A second, much more significant, internal stress is experienced within the graphite components due to irradiation-induced dimensional changes. These induced stresses result from neutron irradiation causing physical changes in the graphite structure, first shrinking it and then expanding it, with increasing neutron dose. This disparity in material volume change can induce significant internal stresses within graphite components. Irradiation-induced creep relaxes these large internal stresses, thus reducing the risk of crack formation and component failure. Obviously, higher irradiation creep levels tend to relieve more internal stress, thus allowing the components longer useful lifetimes within the core. Determining the irradiation creep rates of nuclear graphite grades is critical for determining the useful lifetime of graphite components and is a major component of the advanced graphite creep (AGC) experiment.

The overall AGC experiment is determining the in-service behavior of new graphite grades for use in HTRs. This test series is examining the properties and behaviors of nuclear-grade graphite over a large range of irradiation temperatures, moderate fluence levels, and applied stresses that are expected to induce physical property changes and irradiation creep strains within HTR graphite components. There are six irradiation capsules that will be irradiated in a large flux trap of the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). The AGC irradiation conditions are similar to the anticipated environment within a high-temperature core design. Each irradiation capsule contains over 400 graphite specimens that are characterized before and after irradiation to determine the irradiation-induced material property changes and life-limiting irradiation creep rate for each graphite grade.

The data and information produced in this report and the referenced documents within were generated under the approved quality assurance programs for the respective organizations including INL and Oak Ridge National Laboratory in compliance with the applicable NQA-1 requirements.[4] It is anticipated that all data will be robust enough to stand up to a review by the American Society of Mechanical Engineers and Nuclear Regulatory Commission as support for an eventual graphite reactor design selection.

2. ADVANCED GRAPHITE CREEP EXPERIMENT

The AGC test series is designed to provide data necessary to assist in determining the safe operating envelope of graphite core components for an HTR by measuring the irradiated material property changes and the behavior of several new nuclear graphite grades over a large range of temperatures, moderate neutron fluence, and mechanical compressive loads. The experiment consists of five interrelated stages: pre-irradiation characterization of the graphite specimens, as-run irradiation reports for each test series (designated as six separate irradiation test train capsules), capsule disassembly, post-irradiation examination (PIE) testing, and analysis of the graphite specimens. Separate reports for each distinct stage are prepared after each individual activity is completed.

The pre-irradiation examination report details the total number of graphite grades and individual specimens, specimen loading configuration designed to expose all specimens to the entire range of irradiation conditions, and pre-irradiation material property testing data and results. The as-run irradiation report will detail the irradiation history of each capsule while in the reactor, noting any changes from the technical and functional specifications for each specific test-series capsule and identifying the possible improvements to the next test-series capsule design. The disassembly report details specimen recovery from the irradiation capsule, noting any damage to the specimens and providing an inventory of recovered specimens for PIE testing. The PIE data report (this report) details the changes in specimen dimensional measurements as well as irradiated material properties upon exposure to neutron irradiation. Finally, the PIE analysis report will analyze the irradiation results reported in the data package reports, using the irradiation conditions recorded in the as-run irradiation report. The PIE analysis report(s) determines the irradiation-induced creep rates for the major grades of graphite and assesses any changes to the material properties in all graphite grades. The PIE analysis report(s) interprets the irradiation behavior of graphite to assist in determining a credible, safe operating envelope for graphite core components in an HTR design and licensing application. This report is an AGC PIE data report and provides the results and data from post-irradiation testing for AGC-3 specimens. An abridged statistical analysis is performed here along with a limited comparison to the pre- and post-irradiation data. In this way, the consistency and soundness of the data is initially tested. A more detailed analysis of trends in the AGC-3 PIE data will be reported in the subsequent AGC-3 analysis report(s).

2.1 Design Parameters of AGC Experiment

The AGC test series is designed to measure changes in key thermal, physical, and mechanical material properties over the anticipated range of HTR operating conditions. By comparing the material properties of each specimen before and after irradiation, the experiment generates quantitative material property change data and irradiation creep data that will be used to predict the in-service behavior and operating performance of the current nuclear graphite grades for HTR designs. Specific emphasis is placed on data that account for the life-limiting effects of irradiation creep on graphite components and the effects creep may have on key irradiated material properties of several candidate graphite grades for use in an HTR design.

The critical component of the experiment is the irradiation test series, which irradiates the graphite specimens after pre-irradiation examination characterization has been completed. The AGC test series is comprised of six planned irradiation test trains that are irradiated in ATR in a large flux trap, as described in the graphite technology development plan.[3] The test series exposes test specimens of select nuclear graphite grades to temperatures and the initial range of the expected lifetime irradiation dose that are expected within an HTR design. Specifically, graphite specimens will be exposed to a fast neutron dose ranging from 1 to 7 dpa and temperatures of 600, 800, and 1100°C, as shown in Figure 1. The first and second AGC capsules, AGC-1 and AGC-2, were designed to be irradiated within ATR's south flux trap. All other AGC capsules are to be irradiated within ATR's east flux trap.[5] Generally, irradiations within the south flux trap require approximately 175 effective full-power days to provide a nominal fast neutron dose range (in graphite) of approximately 0.5 to 3.5 dpa. For those capsules requiring a large dose range of approximately 3.5 to 7.0 dpa, the capsule is irradiated for twice as long, approximately 350 effective full-power days.

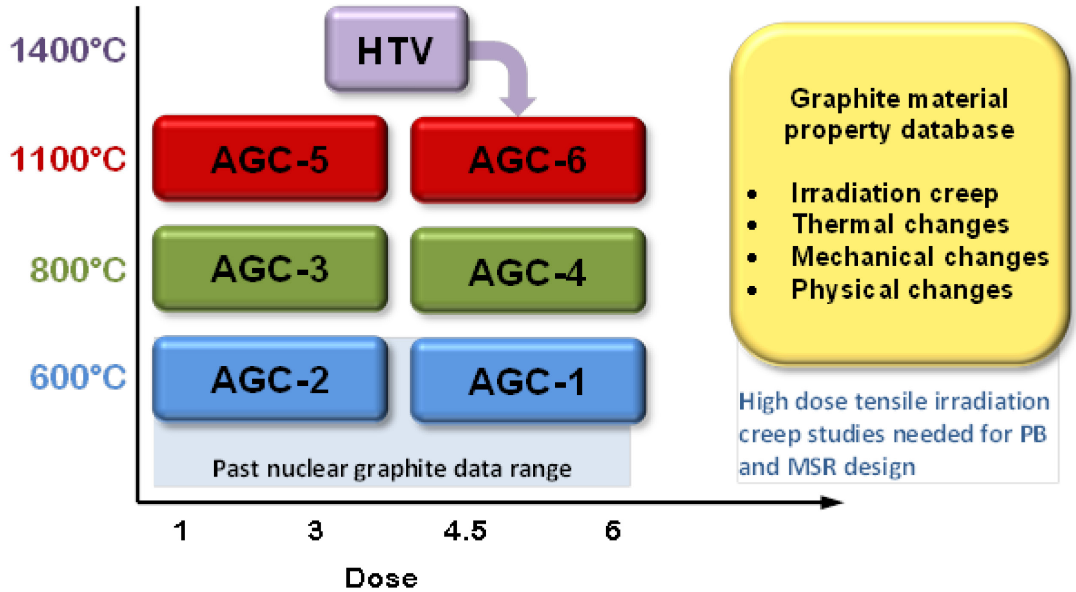

Figure 1. Irradiation dose and temperature parameters for the AGC experiment (MSR is molten salt reactor, HTV is high temperature vessel, and PB is pebble bed).

In addition to determining the irradiation-induced changes to the material properties of selected nuclear graphite grades, the AGC experiment dedicates a significant amount of scope to determining rates of irradiation-induced creep for different nuclear graphite grades. The traditional method for measuring irradiation-induced creep is to apply a significant mechanical load (inducing a mechanical stress within the graphite) to half the specimens during irradiation while leaving the remaining half of the specimens unloaded (unstressed).[6,7] The resulting difference in dimensional change between the loaded and unloaded specimens (assuming that temperature and dose levels are the same) provides the amount of irradiation-induced strain for each "matched pair" of graphite specimens. From this strain level, a creep rate for each graphite grade can be calculated as a function of dose if both specimens were irradiated at the same constant temperature and similar dose level. Thus, each capsule is designed to be irradiated at a constant temperature, allowing only the dose and applied mechanical load to vary within the test train of each test-series capsule. With all graphite specimens at a constant temperature, only the applied stress level and dose will affect the calculated creep rate of each graphite grade within a test-series capsule.

The AGC experiment is designed to measure the constant creep strain rate (secondary creep) of the various grades. The experiment assumes that the induced creep strain for all specimens is within the secondary creep regime and therefore behaves linearly with respect to received neutron dose.[3] This assumption is valid provided the specimens do not go beyond their turnaround dose where creep strain can no longer be expected to be linear with irradiation dose (the onset of tertiary creep). Once the specimens begin to reach turnaround, the creep strain response becomes non-linear with received dose. To ensure specimens remain within the constant linear creep strain regime within AGC-5 and AGC-6 (the highest temperature and dose) test trains, a high-temperature irradiation vessel (HTV) will be used to measure the dimensional changes of the graphite grades at a high temperature (1400°C) and moderate dose (4.5 dpa). Results from this high-temperature dimensional change study will be used in the AGC-5 and AGC-6 designs, which constitute the upper bounds of the AGC experiment (see Figure 1). In addition, if any graphite grade achieves turnaround within the high-temperature irradiation vessel, it will be considered to be outside the upper temperature bounds of the AGC experiment and will be eliminated from the AGC-6 test train.

While the effects from applied mechanical stresses and neutron dose can be determined within each irradiation capsule, the temperature dependency of any irradiation-induced material property changes within the graphite grades is achieved by comparing the measured values of the specimens between irradiation capsules. Since each test train is irradiated at a constant temperature (600, 800, or 1100°C), the temperature-induced/enhanced material property changes must be determined by comparing specimens in different capsules exposed to similar dose and applied mechanical load levels. All AGC capsules are designed to have the same specimen stacking patterns. Thus, if specimens of identical graphite grades are located in similar positions within each capsule, a similar dose and load level will be imposed on a consistent grade of graphite. Maintaining consistent specimen positions for each grade within the six different capsules will allow for the determination of temperature-induced changes for irradiation creep and material properties across the AGC experiment.

2.2 AGC Graphite Grades and Specimen Dimensions

The AGC experiment is designed to ascertain the irradiation behavior of currently available nuclear graphite grades within the anticipated operating parameters of an HTR design. By exposing a variety of nuclear graphite grades representing the range of fabrication parameters (e.g., grain size, fabrication processes, and raw source material) to the expected operating conditions for a moderate HTR design (600 to 1100°C and 0.5 to 7 dpa dose), a comprehensive understanding of the irradiation response and behavior of graphite components in general can be achieved. This will limit the need for additional research in the future if the current graphite grades are altered (i.e., new raw material sources are used) or new grades are used in future reactors.

The AGC experiment uses a variety of current graphite grades to envelope the major fabrication parameters believed to be responsible for the irradiation behavior of nuclear graphite.[1] This range of fabrication parameters is represented by AGC major grades, which were deemed to be production-ready grades that could be used in current or future HTR designs. Major graphite grades are one type of sample within the AGC irradiation capsule. In addition, four other sample types are designated within the AGC experiment. The five AGC sample types are categorized as follows[8]:

1. Major grades (irradiation creep and control specimens). These graphite grades are current reactor candidates for the core structures of an HTR design. Historical, or reference grades, are considered major grades as well. Due to their fabrication maturity and consistency, HTR core components are most likely to be formed from these major grades and are thus expected to receive reasonably large neutron doses in their lifetime. Only major grade specimens were used to determine the critical irradiation-induced creep strain rate.

2. Minor grades (6mm tall, button-shaped piggyback specimens). These grades are HTR-relevant grades that are not yet production ready or are most likely to be used in low-neutron-dose regions of the core (e.g., the permanent structure of the prismatic-block HTR design).

3. Alternate grades (piggyback specimens). Grades that current HTR vendors have identified as being of interest as alternate graphite grades for certain components within the reactor.

4. Experimental grades (piggyback specimens). These graphite grades are included in AGC to assess the viability of new graphite grades whose manufacturing processes and raw materials are such that they may offer superior irradiation stability. Additionally, other carbonaceous materials such as fuel compact matrix materials, carbon-carbon composites, silicon-carbide composites, or other experimental materials that could offer superior performance within the extreme environment of an HTR core are included.

5. Single crystal graphite (piggyback specimens). Samples of highly ordered pyrolytic graphite (HOPG) are included in all AGC capsules to assess the fundamental irradiation response of single crystal graphite. These specimens offer specific dimensional change behavior of graphite, which is particularly significant to the behavior of polycrystalline (polygranular) graphite grades.

To provide all necessary material property tests in the AGC experiment, each test-series capsule contains two primary specimens: (1) “creep” specimens, providing irradiation creep-rate value as well as mechanical properties; and (2) “piggyback” specimens, providing thermal material property changes to the graphite. Creep specimens are fabricated only from major grade graphite types.[2] Piggyback specimens are fabricated from major, minor, and experimental grade graphite types. The piggyback specimens are not mechanically loaded and are subjected only to neutron irradiation at high operating temperatures to assess the effects of a reactor environment on the specific graphite grade.

All specimens are 12.4 mm in diameter, with the larger creep specimens having a nominal length of 25.4 mm and the piggyback specimens having a nominal length of 6.3 mm.[9] Small graphite containers that are 12.4 mm in diameter by 6 mm long contain the thin wafer HOPG specimens, while 12.7-mm-long containers hold the MLRF specimens (experimental silicon-carbide coated graphite specimens from SGL Group being irradiated in AGC-3 capsule only). The large creep specimens provide a means to acquire dimensional/volume change, elastic modulus, thermal expansion, and electrical resistivity measurements. However, these creep specimens are not suitable for thermal diffusivity measurements because of their length. The small piggyback specimens permitted only dimensional measurements, density, and thermal diffusivity testing to be performed. Together, both types of specimens provide the changes in material properties for stressed and unstressed graphite grades.

2.3 General AGC Test Train Design

All AGC test trains and irradiation capsules have the same general physical configuration to provide consistent dose and applied mechanical stresses on specimens of similar graphite grades. While there are key machining and structural differences between capsules to change the irradiation temperature for the different capsules, the majority of the AGC design is identical for all capsules. A schematic of the AGC-3 test train is shown in Figure 2.[9,10,11]

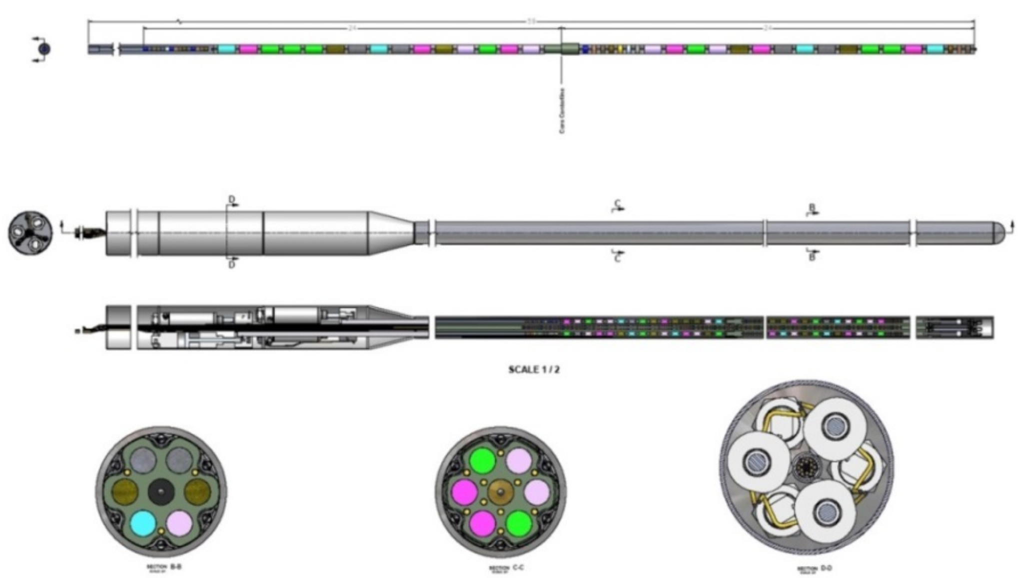

Figure 2. The AGC-3 creep capsule.

All irradiation capsules have six channels located on the outer perimeter of the graphite specimen holder body and a center channel. All channels are 12.9 mm (0.51 in.) in diameter and are designed to hold all types of AGC specimens. The upper (top) half the outer channels has had mechanical loads applied to the specimens. However, the lower (bottom) half for these channels has had no mechanical load applied to the specimens in these locations. Due to the neutron flux profile in ATR, matched pairs with similar neutron fluence and temperatures are achieved by pre-ordering the specimen axial locations. Specimens in the upper half of the channels were stressed by the applied mechanical load while their matched pair received a similar dose in an unstressed state. Three stress levels—13.8, 17.2, and 20.7 MPa (2.0, 2.5, and 3.0 ksi) nominal—are applied in all AGC capsules to provide a known stress upon the graphite specimens during irradiation. These induced stress levels are high enough to produce irradiation-induced creep strain with the graphite specimens. However, the AGC-3 capsule encountered a high gas leak rate (5.6 L/min system leak rate versus the average rate of 1.0 L/min for the AGC-1 and AGC-2 experiments) in the compressive load control system, with the significant increase attributed primarily to the portion of the system providing the load on Stack 4. Therefore, a compressive load was not placed on Stack 4 until the source and future consequences of the leak were evaluated. In addition, a compressive load was not placed on Stack 1 (diametrically opposite and load pair companion to Stack 4) to prevent eccentrically loading the graphite specimen holder, which could possibly result in damaging the holder. The compressive loads on Stacks 2 and 5 were reduced from 17.3 to 13.8 MPa on December 5, 2012, to maximize the range of stack loading from the experiment if Stacks 1 and 4 were not able to have compressive loads.

Since the compressive loads have to remain constant throughout the irradiation, there were two major concerns: (1) the leak rate may increase to the point that the load could not be maintained, and (2) sufficient helium may not be obtainable to overcome the leak rate due to a national shortage of helium. Data from the inlet and outlet system flow meters indicated that the source of the leak was internal to the test train, most probably within the pneumatic ram for Stack 4. After discussions with the vendor and reviewing data taken during preassembly testing of the pneumatic rams, it was decided to test the system to determine the stability of the leak rate. The desired loads were imposed on Stacks 1 and 4 on Tuesday, December 11, 2012, and the leak rate was monitored until Monday, December 17, 2012. The leak rate was extremely stable with essentially no perceptible change over the 6-day period. This result indicated that the leak was most likely located in a metallic component (such as a fitting) and should remain very stable throughout the irradiation. Sufficient helium was located to support maintaining the load on the stacks for the duration of Cycle 152B. The compression gas was switched from helium to argon at the end of Cycle 152B. With the gas shortage issue resolved, and the determination that the leak rate was stable, it was concluded that loads could successfully be applied to Stacks 1 and 4 for the duration of the AGC-3 experiment.

A compressive load of 13.8 MPa was applied to Stacks 1 and 4 for the duration of the experiment. Stacks 2 and 5 remained at 13.8 MPa for the duration of the experiment so that the load applied to these stacks would be constant. Therefore, four stacks were loaded to 13.8 MPa for the experiment and two stacks were loaded to 20.7 MPa (Stacks 3 and 6).[12]

Temperature values within all AGC capsules are calculated based upon thermocouple readings at select positions within the capsule. Specimen temperature is calculated with a finite element model that has been calibrated to predict the known thermocouple readings in the capsule. Dose levels are calculated using Monte Carlo N-Particle Transport Code models and operating conditions in the ATR core and are corroborated from flux wire data.

2.4 Establishing Specimen Dose

To achieve the desired irradiation dose levels and applied mechanical loads to specific specimens, an exact specimen loading order is critical. Because irradiation creep is usually determined by the difference in dimensional change occurring within specimens that have an applied load and those that do not, these matched-pair specimens are assumed to have the same irradiation dose and irradiation temperature values. The AGC test train designs use the symmetric flux profile generated within ATR to achieve these similar irradiation conditions for matched pairs.

Other considerations that went into the capsule design included the size of each creep specimen, need for periodically placed spacers containing flux wires, and space requirements in the top of the stacks for the pneumatic push rods. The core flux mid-plane, in relation to the capsule arrangement, was established so that the reactor neutron flux field could be correlated to the physical elevations and positions in the capsule to yield accurate matched-pair irradiation dose levels (see Figure 3).

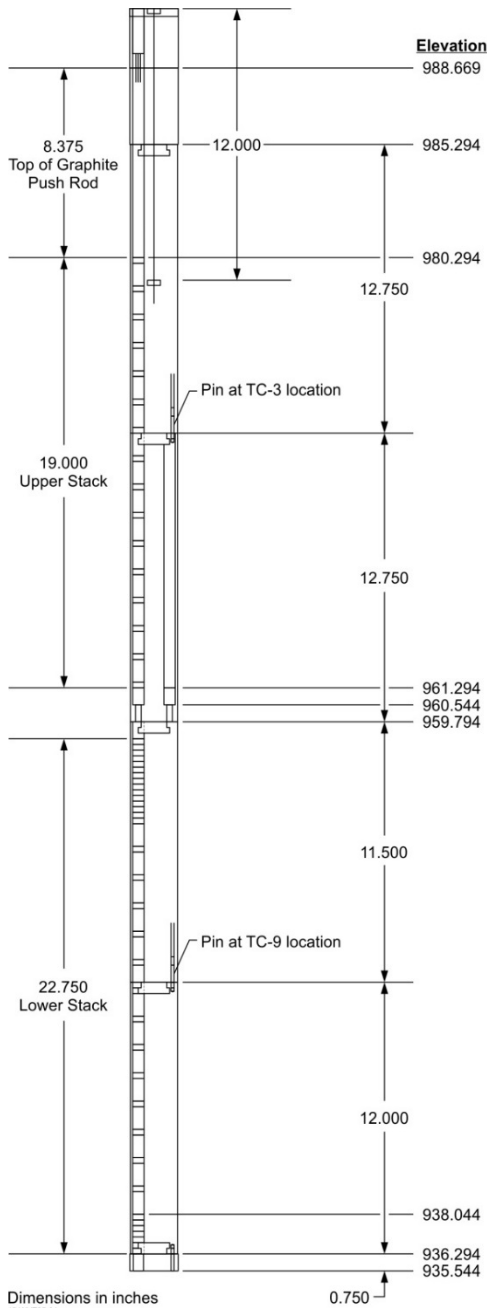

Figure 3. Elevation sketch of the AGC capsule.

Irradiation dose values, as a function of distance from the reactor core centerline, are calculated from the total calculated fluence using standard conversion factors for carbon in a fast neutron irradiation field (E >0.1 MeV).[13] There is a neutron flux gradient across the capsule thickness requiring the capsule to be rotated 180 degrees at the irradiation duration mid-point. This rotation results in a uniform neutron-fluence profile for all stacks, regardless of their position within the capsule.

As described in previous reports,[8] the ATR neutron flux profile is not completely symmetrical along the vertical axis. Thus, to produce matched-pair specimens that have similar dose profiles both above and below the core mid-plane, an offset position from the mid-plane is required. It was determined that an offset distance of 1.25 in. from the core mid-plane for the bottom creep specimens produces the closest dose matches between specimens.

2.5 Physical Positions of Creep Specimens in the Stacks

Once the specimen-position offset is established for the bottom half of the specimens, the number of total creep specimens for each grade of graphite is determined. It should be noted that the specimen stacking order for subsequent AGC irradiation capsules was changed from that initially established for the AGC-1 test train. In the initial AGC capsule design, AGC-1 used 0.25-in.-long NBG-25 graphite spacers between all creep specimens to separate them from each other. It was determined that this was not necessary, and the 0.25-in.-long NBG-25 graphite spacers were eliminated. Eliminating the spacers increased the total number of creep specimens in the AGC capsules. In particular, the number of AGC-3 specimens was increased to 222 total specimens (36 matched pairs in each outer perimeter channel, plus two extra 2114 specimens in each of the first three channels). This allowed more specimens per graphite grade to be irradiated within the AGC-3 capsule.

Because any two opposing stacks are at similar applied stress levels, the specimen loading order can be shifted between the two stacks, allowing the same grade of graphite to be mechanically loaded over a broader neutron dose range, as shown in Figure 4. Assuming that both stacks will have the same applied stress level, receive similar dose levels per position, and have a constant temperature allows this shifting of the specimens and, consequently, a more uniform, smoother dose profile for each graphite grade.

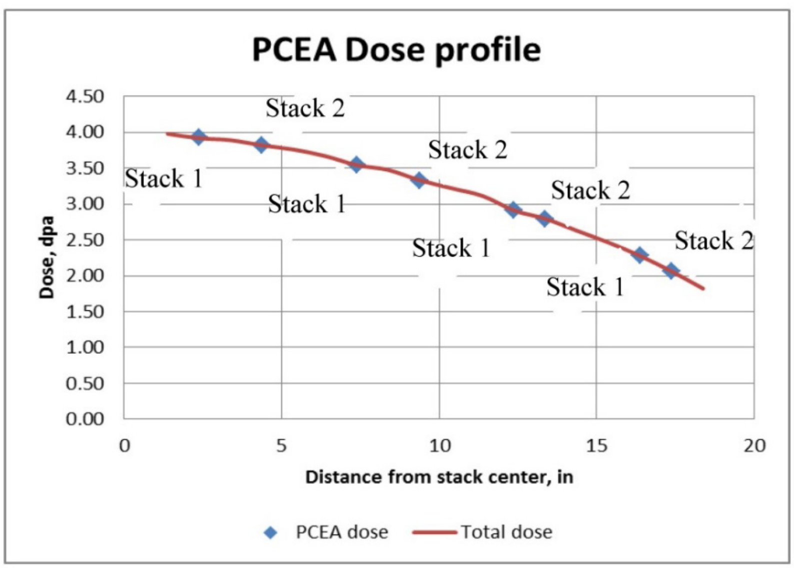

Figure 4. A typical dose profile for creep graphite specimens using similar applied stress levels in matched stacks.

A final consideration when establishing the specimen loading positions is the grain orientation of the specimens. For extruded graphite grades, the against-grain (AG) and with-grain (WG) directions are obviously perpendicular and parallel to the extrusion direction, respectively. Isomolded grades have little to no grain direction, but these specimens were nonetheless machined at two distinct orientations. However, in the case of the vibration-molded graphites (i.e., NBG-17 and NBG-18), there are actually two WG directions and one AG direction as a consequence of the fabrication process. The total number of WG and AG specimens is dependent upon the particular AGC capsule pair (i.e., AGC-1 and AGC-2 have the same number of specimens with similar orientation).

Once these considerations are accounted for, the dose-level profiles are determined for each graphite grade within each channel stack. It should be noted that due to the elimination of the majority of the NBG-25 spacers from the AGC-1 design, the dose-level profiles for each graphite grade have been altered for the succeeding AGC capsules.[13] However, the changes are modest, allowing nearly direct comparison between AGC-1 and the subsequent AGC capsules.

3. AGC-3 TEST TRAIN CAPSULE

The AGC-3 capsule was irradiated in ATR beginning with Cycle 152B on November 27, 2012, and ending with ATR Cycle 155B on April 12, 2014.[12] Between Cycles 154B and 155A, the AGC-3 experiment capsule was rotated 180 degrees to evenly distribute the radiation dose. Estimates of AGC-3 dose, average temperature, and stress conditions are summarized in this report. Specific individual dose levels, temperature ranges, and stress conditions for all specimens contained within the irradiation capsule will be reported in a subsequent AGC-3 analysis report. AGC-3 design documents and drawings pertinent to the AGC-3 graphite specimens have been reported in the previous AGC-3 graphite pre-irradiation data analysis report.[14] The technical and functional requirements for the AGC-3 test train are given in TFR-791.[5]

3.1 AGC-3 Graphite Grades and Changes to Dimensions

Graphite grades used in AGC-3 were categorized as follows:

1. Major graphite grades: 2114, IG-110, NBG-17, NBG-18, and PCEA
2. Minor graphite grades: None
3. Alternate grades: PCIB
4. Experimental grades - Four experimental grades were irradiated in the AGC-3 capsule:
    a. *MLRF* (Hemispherical shaped samples of SGL's NBG-17 grade coated with silicon carbide - SiC)
    b. *SGL/SGL-SiC* (Piggyback button-shaped samples of SGL's NBG-17 grade coated and uncoated with silicon carbide)
    c. *TS* (Piggyback button-shaped samples of a new experimental graphite grade from GrafTech, Inc.)
    d. *PCIB-MG* (Piggyback button-shaped samples of a special experimental formulation of GrafTech, Inc.'s PCIB graphite grade)
5. Single crystal graphite: HOPG.

A more complete description of all of the graphite specimens included in the AGC-3 capsule is given in Table 1.[14]

Table 1. Major, minor, alternate, and experimental graphite grades within the AGC-3 capsule.

Graphite Grade	Forming Method	Intended Purpose	AGC Code Designation

Table 1. (continued).

Graphite Grade	Forming Method	Intended Purpose	AGC Code Designation
NBG-17	Vibrational molded	AREVA Next Generation Nuclear Plant design	A
NBG-18	Vibrational molded	Pebble-Bed Modular Reactor (not currently being pursued)	B
PCEA	Extruded	AREVA Next Generation Nuclear Plant design	D
IG-110	Isostatically pressed	HTR–Pebble-Bed Module (China)	E
HOPG	Vapor deposited	Fundamental studies	CAN101 - CAN117
2114	Isostatically pressed	Candidate graphite	T
PCIB	Isostatically pressed	Alternative candidate grades	P
GrafTech	Isostatically pressed	Alternate/experiment candidate grades TS and PCIB-MG	200,324,325,328
SGL	Vibrational molded	SiC coating experiments	S1-S20
SGL-SiC	Vibrational molded	SiC coating experiments	A-H
MLRF	Vibrational molded	SiC coating experiments	CAN121 – CAN129

3.2 AGC-3 Specimen Stack Positions

The final loading configuration for the outer channel/stacks was determined for each graphite grade to optimize the number of specimens for each grade, create a smooth irradiation profile for the creep and piggyback specimens, and assure the proper position of creep specimens to create the matched pairs. The graphite grades irradiated within AGC-3 differed slightly with the graphite grades in AGC-1 and AGC-2. H-451 and IG-430 were completely removed and replaced with 2114. Table 2 lists the total number of specimens irradiated per major graphite grade.

Table 2. Number of irradiated creep and piggyback specimens of the major grades in the AGC-3 test-series capsule.

Graphite Grade	Creep Specimens	Piggyback Specimens	Total
2114	48	24	72
IG-110	42	29	71
NBG-17	36	30	66
NBG-18	48	20	68
PCEA	48	29	77
Total	222	132	354

The final loading configuration for the AGC-3 capsule is shown in Table 3 through Table 9.[15] These tables also include the specimens' accumulated elevation within the capsule, channel number, and nominal load imposed on the specimens.

Table 3. AGC-3 loading order for Stack 1.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
1	Upper	23	AP3001	Stressed creep	44.000	NBG-17	2
1	Upper	22	1J	Flux Monitor	43.000	-	2
1	Upper	21	DW3001	Stressed creep	42.750	PCEA	2
1	Upper	20	BW3001	Stressed creep	41.750	NBG-18	2
1	Upper	19	EW3001	Stressed creep	40.750	IG-110	2
1	Upper	18	TW3001	Stressed creep	39.750	2114	2
1	Upper	17	DW3004	Stressed creep	38.750	PCEA	2
1	Upper	16	Y1	Flux Monitor	37.750	-	2
1	Upper	15	BP3002	Stressed creep	37.500	NBG-18	2
1	Upper	14	TW3004	Stressed creep	36.500	2114	2
1	Upper	13	EW3004	Stressed creep	35.500	IG-110	2
1	Upper	12	DW3103	Stressed creep	34.500	PCEA	2
1	Upper	11	BW3101	Stressed creep	33.500	NBG-18	2
1	Upper	10	TW3705	Stressed creep	32.500	2114	2
1	Upper	9	DA	Flux Monitor	31.500	-	2
1	Upper	8	AP3301	Stressed creep	31.250	NBG-17	2
1	Upper	7	EW3103	Stressed creep	30.250	IG-110	2
1	Upper	6	DW3203	Stressed creep	29.250	PCEA	2
1	Upper	5	BL3001	Stressed creep	28.250	NBG-18	2
1	Upper	4	TW3010	Stressed creep	27.250	2114	2
1	Upper	3	1L	Flux Monitor	26.250	-	2
1	Upper	2	AW3103	Stressed creep	26.000	NBG-17	2
1	Lower	29	TW3605	Unstressed control	22.500	2114	0
1	Lower	28	200-9	Piggyback	21.500	GrafTech-200	0
1	Lower	27	AW3104	Unstressed control	21.250	NBG-17	0
1	Lower	26	1U	Flux Monitor	20.250	-	0
1	Lower	25	TW3103	Unstressed control	20.000	2114	0
1	Lower	24	BL3004	Unstressed control	19.000	NBG-18	0
1	Lower	23	DW3302	Unstressed control	18.000	PCEA	0
1	Lower	22	EW3202	Unstressed control	17.000	IG-110	0
1	Lower	21	AP3004	Unstressed control	16.000	NBG-17	0
1	Lower	20	AL3804	Piggyback	15.000	NBG-17	0
1	Lower	19	TW3107	Unstressed control	14.750	2114	0
1	Lower	18	BW3501	Unstressed control	13.750	NBG-18	0
1	Lower	17	DW3401	Unstressed control	12.750	PCEA	0
1	Lower	16	EW3301	Unstressed control	11.750	IG-110	0
1	Lower	15	TW3201	Unstressed control	10.750	2114	0
1	Lower	14	BP3005	Unstressed control	9.750	NBG-18	0
1	Lower	13	H7	Flux Monitor	8.750	-	0
1	Lower	12	DW3404	Unstressed control	8.500	PCEA	0
1	Lower	11	TW3402	Unstressed control	7.500	2114	0
1	Lower	10	EW3304	Unstressed control	6.500	IG-110	0
1	Lower	9	BW3301	Unstressed control	5.500	NBG-18	0
1	Lower	8	DW3504	Unstressed control	4.500	PCEA	0
1	Lower	7	F7	Flux Monitor	3.500	-	0
1	Lower	6	AP3202	Unstressed control	3.250	NBG-17	0
1	Lower	5	TW3608	Unstressed control	2.250	2114	0
1	Lower	4	325-12	Piggyback	1.250	GrafTech-325	0
1	Lower	3	200-12	Piggyback	1.000	GrafTech-200	0
1	Lower	2	AL3805	Piggyback	0.750	NBG-17	0

Table 4. AGC-3 loading order for Stack 2.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
2	Upper	23	AP3002	Stressed creep	44.000	NBG-17	2.5
2	Upper	22	EA-SP1	Piggyback Spacer	43.000	IG-110	2.5
2	Upper	21	DW3002	Stressed creep	42.750	PCEA	2.5
2	Upper	20	BW3002	Stressed creep	41.750	NBG-18	2.5
2	Upper	19	EW3802	Stressed creep	40.750	IG-110	2.5
2	Upper	18	TW3002	Stressed creep	39.750	2114	2.5
2	Upper	17	DW3101	Stressed creep	38.750	PCEA	2.5
2	Upper	16	2B	Flux Monitor	37.750	-	2.5
2	Upper	15	BP3003	Stressed creep	37.500	NBG-18	2.5
2	Upper	14	TW3005	Stressed creep	36.500	2114	2.5
2	Upper	13	EW3101	Stressed creep	35.500	IG-110	2.5
2	Upper	12	DW3201	Stressed creep	34.500	PCEA	2.5
2	Upper	11	BW3402	Stressed creep	33.500	NBG-18	2.5
2	Upper	10	TW3008	Stressed creep	32.500	2114	2.5
2	Upper	9	EA-SP2	Piggyback Spacer	31.500	IG-110	2.5
2	Upper	8	AP3302	Stressed creep	31.250	NBG-17	2.5
2	Upper	7	EW3104	Stressed creep	30.250	IG-110	2.5
2	Upper	6	DW3204	Stressed creep	29.250	PCEA	2.5
2	Upper	5	BL3002	Stressed creep	28.250	NBG-18	2.5
2	Upper	4	TW3101	Stressed creep	27.250	2114	2.5
2	Upper	3	FA	Flux Monitor	26.250	-	2.5
2	Upper	2	AW3201	Stressed creep	26.000	NBG-17	2.5
2	Lower	29	TW3606	Unstressed control	22.500	2114	0
2	Lower	28	200-10	Piggyback	21.500	GrafTech-200	0
2	Lower	27	AW3202	Unstressed control	21.250	NBG-17	0
2	Lower	26	EA3609	Piggyback	20.250	IG-110	0
2	Lower	25	TW3105	Unstressed control	20.000	2114	0
2	Lower	24	BL3101	Unstressed control	19.000	NBG-18	0
2	Lower	23	DW3303	Unstressed control	18.000	PCEA	0
2	Lower	22	EW3203	Unstressed control	17.000	IG-110	0
2	Lower	21	AP3101	Unstressed control	16.000	NBG-17	0
2	Lower	20	EA3610	Piggyback	15.000	IG-110	0
2	Lower	19	TW3108	Unstressed control	14.750	2114	0
2	Lower	18	BW3202	Unstressed control	13.750	NBG-18	0
2	Lower	17	DW3402	Unstressed control	12.750	PCEA	0
2	Lower	16	EW3302	Unstressed control	11.750	IG-110	0
2	Lower	15	TW3202	Unstressed control	10.750	2114	0
2	Lower	14	BP3101	Unstressed control	9.750	NBG-18	0
2	Lower	13	7O	Flux Monitor	8.750	-	0
2	Lower	12	DW3501	Unstressed control	8.500	PCEA	0
2	Lower	11	TW3403	Unstressed control	7.500	2114	0
2	Lower	10	EW3401	Unstressed control	6.500	IG-110	0
2	Lower	9	BW3503	Unstressed control	5.500	NBG-18	0
2	Lower	8	DW3601	Unstressed control	4.500	PCEA	0
2	Lower	7	EA3611	Piggyback	3.500	IG-110	0
2	Lower	6	AP3203	Unstressed control	3.250	NBG-17	0
2	Lower	5	TW3609	Unstressed control	2.250	2114	0
2	Lower	4	325-13	Piggyback	1.250	GrafTech-325	0
2	Lower	3	200-13	Piggyback	1.000	GrafTech-200	0
2	Lower	2	AL3806	Piggyback	0.750	NBG-17	0

Table 5. AGC-3 loading order for Stack 3.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
3	Upper	23	AP3003	Stressed creep	44.000	NBG-17	3
3	Upper	22	EW-SP1	Piggyback Spacer	43.000	IG-110	3
3	Upper	21	DW3003	Stressed creep	42.750	PCEA	3
3	Upper	20	BW3401	Stressed creep	41.750	NBG-18	3
3	Upper	19	EW3003	Stressed creep	40.750	IG-110	3
3	Upper	18	TW3003	Stressed creep	39.750	2114	3
3	Upper	17	DW3102	Stressed creep	38.750	PCEA	3
3	Upper	16	AF	Flux Monitor	37.750	-	3
3	Upper	15	BP3004	Stressed creep	37.500	NBG-18	3
3	Upper	14	TW3006	Stressed creep	36.500	2114	3
3	Upper	13	EW3801	Stressed creep	35.500	IG-110	3
3	Upper	12	DW3202	Stressed creep	34.500	PCEA	3
3	Upper	11	BW3103	Stressed creep	33.500	NBG-18	3
3	Upper	10	TW3009	Stressed creep	32.500	2114	3
3	Upper	9	EW-SP2	Piggyback Spacer	31.500	IG-110	3
3	Upper	8	AP3303	Stressed creep	31.250	NBG-17	3
3	Upper	7	EW3201	Stressed creep	30.250	IG-110	3
3	Upper	6	DW3301	Stressed creep	29.250	PCEA	3
3	Upper	5	BL3003	Stressed creep	28.250	NBG-18	3
3	Upper	4	TW3102	Stressed creep	27.250	2114	3
3	Upper	3	8I	Flux Monitor	26.250	-	3
3	Upper	2	AW3203	Stressed creep	26.000	NBG-17	3
3	Lower	29	TW3607	Unstressed control	22.500	2114	0
3	Lower	28	200-11	Piggyback	21.500	GrafTech-200	0
3	Lower	27	AW3204	Unstressed control	21.250	NBG-17	0
3	Lower	26	EW4607	Piggyback	20.250	IG-110	0
3	Lower	25	TW3106	Unstressed control	20.000	2114	0
3	Lower	24	BL3102	Unstressed control	19.000	NBG-18	0
3	Lower	23	DW3304	Unstressed control	18.000	PCEA	0
3	Lower	22	EW3204	Unstressed control	17.000	IG-110	0
3	Lower	21	AP3102	Unstressed control	16.000	NBG-17	0
3	Lower	20	EW4608	Piggyback	15.000	IG-110	0
3	Lower	19	TW3109	Unstressed control	14.750	2114	0
3	Lower	18	BW3502	Unstressed control	13.750	NBG-18	0
3	Lower	17	DW3403	Unstressed control	12.750	PCEA	0
3	Lower	16	EW3303	Unstressed control	11.750	IG-110	0
3	Lower	15	TW3704	Unstressed control	10.750	2114	0
3	Lower	14	BP3102	Unstressed control	9.750	NBG-18	0
3	Lower	13	XA	Flux Monitor	8.750	-	0
3	Lower	12	DW3502	Unstressed control	8.500	PCEA	0
3	Lower	11	TW3404	Unstressed control	7.500	2114	0
3	Lower	10	EW3402	Unstressed control	6.500	IG-110	0
3	Lower	9	BW3303	Unstressed control	5.500	NBG-18	0
3	Lower	8	DW3602	Unstressed control	4.500	PCEA	0
3	Lower	7	EW4609	Piggyback	3.500	IG-110	0
3	Lower	6	AP3204	Unstressed control	3.250	NBG-17	0
3	Lower	5	TW3610	Unstressed control	2.250	2114	0
3	Lower	4	325-14	Piggyback	1.250	GrafTech-325	0
3	Lower	3	200-14	Piggyback	1.000	GrafTech-200	0
3	Lower	2	AL3807	Piggyback	0.750	NBG-17	0

Table 6. AGC-3 loading order for Stack 4.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
4	Upper	23	EW3601	Stressed creep	44.000	IG-110	2
4	Upper	22	7A	Flux Monitor	43.000	-	2
4	Upper	21	TW3703	Stressed creep	42.750	2114	2
4	Upper	20	DA3001	Stressed creep	41.750	PCEA	2
4	Upper	19	BP3103	Stressed creep	40.750	NBG-18	2
4	Upper	18	AL3202	Stressed creep	39.750	NBG-17	2
4	Upper	17	EW3604	Stressed creep	38.750	IG-110	2
4	Upper	16	1H	Flux Monitor	37.750	-	2
4	Upper	15	DW3801	Stressed creep	37.500	PCEA	2
4	Upper	14	BL3103	Stressed creep	36.500	NBG-18	2
4	Upper	13	TW3405	Stressed creep	35.500	2114	2
4	Upper	12	AW3001	Stressed creep	34.500	NBG-17	2
4	Upper	11	EA3001	Stressed creep	33.500	IG-110	2
4	Upper	10	DA3203	Stressed creep	32.500	PCEA	2
4	Upper	9	YA	Flux Monitor	31.500	-	2
4	Upper	8	BP3202	Stressed creep	31.250	NBG-18	2
4	Upper	7	TW3408	Stressed creep	30.250	2114	2
4	Upper	6	AP3304	Stressed creep	29.250	NBG-17	2
4	Upper	5	EA3004	Stressed creep	28.250	IG-110	2
4	Upper	4	DW3603	Stressed creep	27.250	PCEA	2
4	Upper	3	1C	Flux Monitor	26.250	-	2
4	Upper	2	BP3301	Stressed creep	26.000	NBG-18	2
4	Lower	35	AW3810	Piggyback	22.500	NBG-17	0
4	Lower	34	EW4601	Piggyback	22.250	IG-110	0
4	Lower	33	TW3821	Piggyback	22.000	2114	0
4	Lower	32	325-9	Piggyback	21.750	GrafTech-325	0
4	Lower	31	P3-07	Piggyback	21.500	PCIB	0
4	Lower	30	BP3304	Unstressed control	21.250	NBG-18	0
4	Lower	29	R7	Flux Monitor	20.250	-	0
4	Lower	28	DW3702	Unstressed control	20.000	PCEA	0
4	Lower	27	EA3103	Unstressed control	19.000	IG-110	0
4	Lower	26	AP3403	Unstressed control	18.000	NBG-17	0
4	Lower	25	TW3501	Unstressed control	17.000	2114	0
4	Lower	24	BP3603	Unstressed control	16.000	NBG-18	0
4	Lower	23	TW3904	Piggyback	15.000	2114	0
4	Lower	22	DA3302	Unstressed control	14.750	PCEA	0
4	Lower	21	EA3202	Unstressed control	13.750	IG-110	0
4	Lower	20	AW3004	Unstressed control	12.750	NBG-17	0
4	Lower	19	TW3504	Unstressed control	11.750	2114	0
4	Lower	18	BL3201	Unstressed control	10.750	NBG-18	0
4	Lower	17	DW3803	Unstressed control	9.750	PCEA	0
4	Lower	16	1O	Flux Monitor	8.750	-	0
4	Lower	15	EW3403	Unstressed control	8.500	IG-110	0
4	Lower	14	AL3301	Unstressed control	7.500	NBG-17	0
4	Lower	13	BP3801	Unstressed control	6.500	NBG-18	0
4	Lower	12	DA3403	Unstressed control	5.500	PCEA	0
4	Lower	11	TW3507	Unstressed control	4.500	2114	0
4	Lower	10	JA	Flux Monitor	3.500	-	0
4	Lower	9	EW3502	Unstressed control	3.250	IG-110	0
4	Lower	8	BL3601	Piggyback	2.250	NBG-18	0
4	Lower	7	AL3801	Piggyback	2.000	NBG-17	0
4	Lower	6	EW4509	Piggyback	1.750	IG-110	0
4	Lower	5	AL3904	Piggyback	1.500	NBG-17	0
4	Lower	4	DW4511	Piggyback	1.250	PCEA	0
4	Lower	3	DA3510	Piggyback	1.000	PCEA	0
4	Lower	2	TW3827	Piggyback	0.750	2114	0

Table 7. AGC-3 loading order for Stack 5.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
5	Upper	23	EW3602	Stressed creep	44.000	IG-110	2.5
5	Upper	22	DA-SP1	Piggyback Spacer	44.000	PCEA	2.5
5	Upper	21	TW3702	Stressed creep	42.750	2114	2.5
5	Upper	20	DA3003	Stressed creep	41.750	PCEA	2.5
5	Upper	19	BP3104	Stressed creep	40.750	NBG-18	2.5
5	Upper	18	AL3203	Stressed creep	39.750	NBG-17	2.5
5	Upper	17	EW3701	Stressed creep	38.750	IG-110	2.5
5	Upper	16	J7	Flux Monitor	37.750	-	2.5
5	Upper	15	DW3804	Stressed creep	37.500	PCEA	2.5
5	Upper	14	BL3104	Stressed creep	36.500	NBG-18	2.5
5	Upper	13	TW3406	Stressed creep	35.500	2114	2.5
5	Upper	12	AW3002	Stressed creep	34.500	NBG-17	2.5
5	Upper	11	EA3002	Stressed creep	33.500	IG-110	2.5
5	Upper	10	DA3204	Stressed creep	32.500	PCEA	2.5
5	Upper	9	DA-SP2	Piggyback Spacer	31.500	PCEA	2.5
5	Upper	8	BP3204	Stressed creep	31.250	NBG-18	2.5
5	Upper	7	TW3409	Stressed creep	30.250	2114	2.5
5	Upper	6	AP3401	Stressed creep	29.250	NBG-17	2.5
5	Upper	5	EA3101	Stressed creep	28.250	IG-110	2.5
5	Upper	4	DW3604	Stressed creep	27.250	PCEA	2.5
5	Upper	3	O7	Flux Monitor	26.250	-	2.5
5	Upper	2	BP3302	Stressed creep	26.000	NBG-18	2.5
5	Lower	35	AW3811	Piggyback	22.500	NBG-17	0
5	Lower	34	EW4602	Piggyback	22.250	IG-110	0
5	Lower	33	TW3822	Piggyback	22.000	2114	0
5	Lower	32	325-10	Piggyback	21.750	GrafTech-325	0
5	Lower	31	P3-08	Piggyback	21.500	PCIB	0
5	Lower	30	BP3601	Unstressed control	21.250	NBG-18	0
5	Lower	29	DA3603	Piggyback	20.250	PCEA	0
5	Lower	28	DW3703	Unstressed control	20.000	PCEA	0
5	Lower	27	EA3104	Unstressed control	19.000	IG-110	0
5	Lower	26	AP3404	Unstressed control	18.000	NBG-17	0
5	Lower	25	TW3502	Unstressed control	17.000	2114	0
5	Lower	24	BP3604	Unstressed control	16.000	NBG-18	0
5	Lower	23	DA3604	Piggyback	15.000	PCEA	0
5	Lower	22	DA3303	Unstressed control	14.750	PCEA	0
5	Lower	21	EA3203	Unstressed control	13.750	IG-110	0
5	Lower	20	AW3101	Unstressed control	12.750	NBG-17	0
5	Lower	19	TW3505	Unstressed control	11.750	2114	0
5	Lower	18	BL3202	Unstressed control	10.750	NBG-18	0
5	Lower	17	DW3901	Unstressed control	9.750	PCEA	0
5	Lower	16	Y2	Flux Monitor	8.750	-	0
5	Lower	15	EW3704	Unstressed control	8.500	IG-110	0
5	Lower	14	AL3101	Unstressed control	7.500	NBG-17	0
5	Lower	13	BP3702	Unstressed control	6.500	NBG-18	0
5	Lower	12	DA3404	Unstressed control	5.500	PCEA	0
5	Lower	11	TW3508	Unstressed control	4.500	2114	0
5	Lower	10	DA3605	Piggyback	3.500	PCEA	0
5	Lower	9	EW3503	Unstressed control	3.250	IG-110	0
5	Lower	8	BL3602	Piggyback	2.250	NBG-18	0
5	Lower	7	AL3802	Piggyback	2.000	NBG-17	0
5	Lower	6	EW4510	Piggyback	1.750	IG-110	0
5	Lower	5	AW3902	Piggyback	1.500	NBG-17	0
5	Lower	4	DW4512	Piggyback	1.250	PCEA	0
5	Lower	3	DA3511	Piggyback	1.000	PCEA	0
5	Lower	2	TW3828	Piggyback	0.750	2114	0

Table 8. AGC-3 loading order for Stack 6.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
6	Upper	23	EW3603	Stressed creep	44.000	IG-110	3
6	Upper	22	DA-SP3	Piggyback Spacer	43.000	PCEA	3
6	Upper	21	TW3602	Stressed creep	42.750	2114	3
6	Upper	20	DA3004	Stressed creep	41.750	PCEA	3
6	Upper	19	BP3201	Stressed creep	40.750	NBG-18	3
6	Upper	18	AL3204	Stressed creep	39.750	NBG-17	3
6	Upper	17	EW3702	Stressed creep	38.750	IG-110	3
6	Upper	16	AU	Flux Monitor	37.750	-	3
6	Upper	15	DW3902	Stressed creep	37.500	PCEA	3
6	Upper	14	BL3204	Stressed creep	36.500	NBG-18	3
6	Upper	13	TW3407	Stressed creep	35.500	2114	3
6	Upper	12	AW3003	Stressed creep	34.500	NBG-17	3
6	Upper	11	EA3003	Stressed creep	33.500	IG-110	3
6	Upper	10	DA3301	Stressed creep	32.500	PCEA	3
6	Upper	9	DA-SP4	Piggyback Spacer	31.500	PCEA	3
6	Upper	8	BP3205	Stressed creep	31.250	NBG-18	3
6	Upper	7	TW3410	Stressed creep	30.250	2114	3
6	Upper	6	AP3402	Stressed creep	29.250	NBG-17	3
6	Upper	5	EA3301	Stressed creep	28.250	IG-110	3
6	Upper	4	DW3701	Stressed creep	27.250	PCEA	3
6	Upper	3	1D	Flux Monitor	26.250	-	3
6	Upper	2	BP3303	Stressed creep	26.000	NBG-18	3
6	Lower	35	AW3812	Piggyback	22.500	NBG-17	0
6	Lower	34	EW4603	Piggyback	22.250	IG-110	0
6	Lower	33	TW3823	Piggyback	22.000	2114	0
6	Lower	32	325-11	Piggyback	21.750	GrafTech-325	0
6	Lower	31	P3-09	Piggyback	21.500	PCIB	0
6	Lower	30	BP3602	Unstressed control	21.250	NBG-18	0
6	Lower	29	DA3608	Piggyback	20.250	PCEA	0
6	Lower	28	DW3704	Unstressed control	20.000	PCEA	0
6	Lower	27	EA3201	Unstressed control	19.000	IG-110	0
6	Lower	26	AP3103	Unstressed control	18.000	NBG-17	0
6	Lower	25	TW3503	Unstressed control	17.000	2114	0
6	Lower	24	BP3605	Unstressed control	16.000	NBG-18	0
6	Lower	23	DA3607	Piggyback	15.000	PCEA	0
6	Lower	22	DA3401	Unstressed control	14.750	PCEA	0
6	Lower	21	EA3204	Unstressed control	13.750	IG-110	0
6	Lower	20	AW3102	Unstressed control	12.750	NBG-17	0
6	Lower	19	TW3506	Unstressed control	11.750	2114	0
6	Lower	18	BL3203	Unstressed control	10.750	NBG-18	0
6	Lower	17	DW3903	Unstressed control	9.750	PCEA	0
6	Lower	16	AH	Flux Monitor	8.750	-	0
6	Lower	15	EW3501	Unstressed control	8.500	IG-110	0
6	Lower	14	AL3103	Unstressed control	7.500	NBG-17	0
6	Lower	13	BP3703	Unstressed control	6.500	NBG-18	0
6	Lower	12	DA3104	Unstressed control	5.500	PCEA	0
6	Lower	11	TW3509	Unstressed control	4.500	2114	0
6	Lower	10	DA3606	Piggyback	3.500	PCEA	0
6	Lower	9	EW3504	Unstressed control	3.250	IG-110	0
6	Lower	8	BL3603	Piggyback	2.250	NBG-18	0
6	Lower	7	AL3803	Piggyback	2.000	NBG-17	0
6	Lower	6	EW4511	Piggyback	1.750	IG-110	0
6	Lower	5	AW3903	Piggyback	1.500	NBG-17	0
6	Lower	4	DW4601	Piggyback	1.250	PCEA	0
6	Lower	3	DA3512	Piggyback	1.000	PCEA	0
6	Lower	2	TW3829	Piggyback	0.750	2114	0

Table 9. AGC-3 loading order for Stack 7.

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
7	Center	161	BP3401	Piggyback	42.500	NBG-18	0
7	Center	160	AP3501	Piggyback	42.250	NBG-17	0
7	Center	159	EA3504	Piggyback	42.000	IG-110	0
7	Center	158	TW3801	Piggyback	41.750	2114	0
7	Center	157	DA3501	Piggyback	41.500	PCEA	0
7	Center	156	CAN101	CAN	41.250	HOPG	0
7	Center	155	CAN129	CAN	41.000	MLRF	0
7	Center	154	324-1	Piggyback	40.500	GrafTech-324	0
7	Center	153	328-1	Piggyback	40.250	GrafTech-328	0
7	Center	152	BW4002	Piggyback	40.000	NBG-18	0
7	Center	151	AW3801	Piggyback	39.750	NBG-17	0
7	Center	150	EW4501	Piggyback	39.500	IG-110	0
7	Center	149	TW3802	Piggyback	39.250	2114	0
7	Center	148	DW4502	Piggyback	39.000	PCEA	0
7	Center	147	CAN102	CAN	38.750	HOPG	0
7	Center	146	A	Piggyback	38.500	SGL-SiC	0
7	Center	145	S1	Piggyback	38.250	SGL	0
7	Center	144	325-1	Piggyback	38.000	GrafTech-325	0
7	Center	143	200-1	Piggyback	37.750	GrafTech-200	0
7	Center	142	BP3502	Piggyback	37.500	NBG-18	0
7	Center	141	AP3502	Piggyback	37.250	NBG-17	0
7	Center	140	EA3505	Piggyback	37.000	IG-110	0
7	Center	139	TW3803	Piggyback	36.750	2114	0
7	Center	138	DA3502	Piggyback	36.500	PCEA	0
7	Center	137	CAN103	CAN	36.250	HOPG	0
7	Center	136	CAN121	CAN	36.000	MLRF	0
7	Center	135	324-2	Piggyback	35.500	GrafTech-324	0
7	Center	134	328-2	Piggyback	35.250	GrafTech-328	0
7	Center	133	BW4003	Piggyback	35.000	NBG-18	0
7	Center	132	AW3802	Piggyback	34.750	NBG-17	0
7	Center	131	EW4502	Piggyback	34.500	IG-110	0
7	Center	130	TW3804	Piggyback	34.250	2114	0
7	Center	129	DW4503	Piggyback	34.000	PCEA	0
7	Center	128	CAN104	CAN	33.750	HOPG	0
7	Center	127	B	Piggyback	33.500	SGL-SiC	0
7	Center	126	S2	Piggyback	33.250	SGL	0
7	Center	125	325-2	Piggyback	33.000	GrafTech-325	0
7	Center	124	200-2	Piggyback	32.750	GrafTech-200	0
7	Center	123	BP3403	Piggyback	32.500	NBG-18	0
7	Center	122	AP3503	Piggyback	32.250	NBG-17	0
7	Center	121	EA3506	Piggyback	32.000	IG-110	0
7	Center	120	TW3805	Piggyback	31.750	2114	0
7	Center	119	DA3503	Piggyback	31.500	PCEA	0
7	Center	118	CAN105	CAN	31.250	HOPG	0
7	Center	117	CAN122	CAN	31.000	MLRF	0
7	Center	116	324-3	Piggyback	30.500	GrafTech-324	0
7	Center	115	328-3	Piggyback	30.250	GrafTech-328	0
7	Center	114	BW4004	Piggyback	30.000	NBG-18	0
7	Center	113	AW3803	Piggyback	29.750	NBG-17	0
7	Center	112	EW4503	Piggyback	29.500	IG-110	0
7	Center	111	TW3806	Piggyback	29.250	2114	0
7	Center	110	DW4504	Piggyback	29.000	PCEA	0
7	Center	109	CAN106	CAN	28.750	HOPG	0
7	Center	108	C	Piggyback	28.500	SGL-SiC	0
7	Center	107	S3	Piggyback	28.250	SGL	0

Table 9. (continued).

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
7	Center	106	325-3	Piggyback	28.000	GrafTech-325	0
7	Center	105	200-3	Piggyback	27.750	GrafTech-200	0
7	Center	104	BP3404	Piggyback	27.500	NBG-18	0
7	Center	103	AP3504	Piggyback	27.250	NBG-17	0
7	Center	102	EA3507	Piggyback	27.000	IG-110	0
7	Center	101	TW3807	Piggyback	26.750	2114	0
7	Center	100	DA3504	Piggyback	26.500	PCEA	0
7	Center	99	CAN107	CAN	26.250	HOPG	0
7	Center	98	CAN123	CAN	26.000	MLRF	0
7	Center	97	324-4	Piggyback	25.500	GrafTech-324	0
7	Center	96	328-4	Piggyback	25.250	GrafTech-328	0
7	Center	95	BW4005	Piggyback	25.000	NBG-18	0
7	Center	94	AW3804	Piggyback	24.750	NBG-17	0
7	Center	93	EW4504	Piggyback	24.500	IG-110	0
7	Center	92	TW3808	Piggyback	24.250	2114	0
7	Center	91	DW4505	Piggyback	24.000	PCEA	0
7	Center	90	CAN108	CAN	23.750	HOPG	0
7	Center	89	D	Piggyback	23.500	SGL-SiC	0
7	Center	88	S4	Piggyback	23.250	SGL	0
7	Center	87	325-4	Piggyback	23.000	GrafTech-325	0
7	Center	86	200-4	Piggyback	22.750	GrafTech-200	0
7	Center	85	BP3405	Piggyback	22.500	NBG-18	0
7	Center	84	AP3505	Piggyback	22.250	NBG-17	0
7	Center	83	EA3508	Piggyback	22.000	IG-110	0
7	Center	82	TW3809	Piggyback	21.750	2114	0
7	Center	81	DA3505	Piggyback	21.500	PCEA	0
7	Center	80	CAN109	CAN	21.250	HOPG	0
7	Center	79	CAN124	CAN	21.000	MLRF	0
7	Center	78	324-5	Piggyback	20.500	GrafTech-324	0
7	Center	77	328-5	Piggyback	20.250	GrafTech-328	0
7	Center	76	BW4006	Piggyback	20.000	NBG-18	0
7	Center	75	AW3805	Piggyback	19.750	NBG-17	0
7	Center	74	EW4505	Piggyback	19.500	IG-110	0
7	Center	73	TW3810	Piggyback	19.250	2114	0
7	Center	72	DW4506	Piggyback	19.000	PCEA	0
7	Center	71	CAN110	CAN	18.750	HOPG	0
7	Center	70	E	Piggyback	18.500	SGL-SiC	0
7	Center	69	S5	Piggyback	18.250	SGL	0
7	Center	68	325-5	Piggyback	18.000	GrafTech-325	0
7	Center	67	200-5	Piggyback	17.750	GrafTech-200	0
7	Center	66	BP3406	Piggyback	17.500	NBG-18	0
7	Center	65	AP3506	Piggyback	17.250	NBG-17	0
7	Center	64	EA3509	Piggyback	17.000	IG-110	0
7	Center	63	TW3811	Piggyback	16.750	2114	0
7	Center	62	DA3506	Piggyback	16.500	PCEA	0
7	Center	61	CAN111	CAN	16.250	HOPG	0
7	Center	60	CAN125	CAN	16.000	MLRF	0
7	Center	59	324-6	Piggyback	15.500	GrafTech-324	0
7	Center	58	328-6	Piggyback	15.250	GrafTech-328	0
7	Center	57	BW4007	Piggyback	15.000	NBG-18	0
7	Center	56	AW3806	Piggyback	14.750	NBG-17	0
7	Center	55	EW4506	Piggyback	14.500	IG-110	0
7	Center	54	TW3812	Piggyback	14.250	2114	0
7	Center	53	DW4507	Piggyback	14.000	PCEA	0
7	Center	52	CAN112	CAN	13.750	HOPG	0

Table 9. (continued).

Channel	Housing	Loading Order	Specimen ID	Description	Accumulative Elevation (in)	Grade	Nominal Load (KSI)
7	Center	51	F	Piggyback	13.500	SGL-SiC	0
7	Center	50	S6	Piggyback	13.250	SGL	0
7	Center	49	325-6	Piggyback	13.000	GrafTech-325	0
7	Center	48	200-6	Piggyback	12.750	GrafTech-200	0
7	Center	47	BP3407	Piggyback	12.500	NBG-18	0
7	Center	46	AP3507	Piggyback	12.250	NBG-17	0
7	Center	45	EA3510	Piggyback	12.000	IG-110	0
7	Center	44	TW3813	Piggyback	11.750	2114	0
7	Center	43	DA3507	Piggyback	11.500	PCEA	0
7	Center	42	CAN113	CAN	11.250	HOPG	0
7	Center	41	CAN126	CAN	11.000	MLRF	0
7	Center	40	324-7	Piggyback	10.500	GrafTech-324	0
7	Center	39	328-7	Piggyback	10.250	GrafTech-328	0
7	Center	38	BW4101	Piggyback	10.000	NBG-18	0
7	Center	37	AW3808	Piggyback	9.750	NBG-17	0
7	Center	36	EW4507	Piggyback	9.500	IG-110	0
7	Center	35	TW3814	Piggyback	9.250	2114	0
7	Center	34	DW4508	Piggyback	9.000	PCEA	0
7	Center	33	CAN114	CAN	8.750	HOPG	0
7	Center	32	G	Piggyback	8.500	SGL-SiC	0
7	Center	31	S7	Piggyback	8.250	SGL	0
7	Center	30	325-7	Piggyback	8.000	GrafTech-325	0
7	Center	29	200-7	Piggyback	7.750	GrafTech-200	0
7	Center	28	BP3408	Piggyback	7.500	NBG-18	0
7	Center	27	AP3508	Piggyback	7.250	NBG-17	0
7	Center	26	EA3511	Piggyback	7.000	IG-110	0
7	Center	25	TW3815	Piggyback	6.750	2114	0
7	Center	24	DA3508	Piggyback	6.500	PCEA	0
7	Center	23	CAN115	CAN	6.250	HOPG	0
7	Center	22	CAN127	CAN	6.000	MLRF	0
7	Center	21	324-8	Piggyback	5.500	GrafTech-324	0
7	Center	20	328-8	Piggyback	5.250	GrafTech-328	0
7	Center	19	BW4102	Piggyback	5.000	NBG-18	0
7	Center	18	AW3809	Piggyback	4.750	NBG-17	0
7	Center	17	EW4508	Piggyback	4.500	IG-110	0
7	Center	16	TW3816	Piggyback	4.250	2114	0
7	Center	15	DW4509	Piggyback	4.000	PCEA	0
7	Center	14	CAN116	CAN	3.750	HOPG	0
7	Center	13	H	Piggyback	3.500	SGL-SiC	0
7	Center	12	S8	Piggyback	3.250	SGL	0
7	Center	11	325-8	Piggyback	3.000	GrafTech-325	0
7	Center	10	200-8	Piggyback	2.750	GrafTech-200	0
7	Center	9	BP3409	Piggyback	2.500	NBG-18	0
7	Center	8	AP3509	Piggyback	2.250	NBG-17	0
7	Center	7	EA3512	Piggyback	2.000	IG-110	0
7	Center	6	TW3817	Piggyback	1.750	2114	0
7	Center	5	DA3509	Piggyback	1.500	PCEA	0
7	Center	4	CAN117	CAN	1.250	HOPG	0
7	Center	3	CAN128	CAN	1.000	MLRF	0
7	Center	2	324-9	Piggyback	0.500	GrafTech-324	0
7	Center	1	328-9	Piggyback	0.250	GrafTech-328	0

Following irradiation in ATR at INL, the AGC-3 capsule was disassembled.[16] All specimens recovered from disassembly were visually inspected and physically measured within the INL Carbon Characterization Laboratory before storage within the irradiated graphite storage vault. It should be noted that one 2114 specimen (TW3405) and two NBG-17 specimens (BL3103 and BP3302) were lost during AGC-3 disassembly activities. After accounting for all recovered specimens from the AGC-3 capsule, PIE and testing were performed for each specimen in the INL Carbon Characterization Laboratory.

4. TESTING

A significant level of preparation was needed to meet the NQA-1 quality requirements prior to actual material property testing. An approved characterization plan was developed that was dependent upon the two graphite specimen geometries and on the material properties to be measured.[17,18] In general, all testing was performed through American Society for Testing and Materials (ASTM) approved standards; however, due to the small size of the graphite specimens, some methods required modification and/or variation of the testing standards. Details of these testing standard variations, along with equipment calibration, personnel training on testing methodology, and data acquisition, are specified in the characterization plans.

Thermal diffusivity, coefficient of thermal expansion (CTE), electrical resistivity, elastic modulus, mass, and dimensional measurements were performed on the AGC-3 irradiated specimens. These measurements were performed per the AGC-3 graphite specimen post-irradiation characterization plan.[18] This plan describes in detail the measurement techniques, equipment, and standards used to gather the data presented here.

Data gathered for the characterization of AGC-3 specimens are contained in the appendixes of this report. Appendix A contains plots of the individual data points for each specimen. Shown by the dashed lines in each plot are the upper and lower limits of the interquartile range (IQR). These limits are established by either the least or greatest value in the data or by multiplying the IQR by 1.5 and adding or subtracting this value from the third and first quartile. Any datum value outside of these established limits is considered a suspected outlier of the established pattern and may indicate a mistaken measurement test or calculated value. Any sample exhibiting a measured data point outside of the established pattern is reassessed, including re-testing the specific material property value, to ascertain whether the sample was tested correctly. It is important to note that the analysis of these outlying values are not meant to determine the changes due to irradiation (i.e., variations resulting from different grades, received dose, temperature, orientation, and/or applied stress). A complete analysis addressing the irradiation conditions will be provided in a future data analysis report.

These outlying values are examined in the context of the entire data set, including pre-irradiation data. Other statistical parameters are calculated and presented in the tables of Appendix B. The mean, standard deviation, and coefficient of variance (COV) are all calculated for the various measurement data sets and graphite types. Upper and lower limits displayed in the tables of Appendix B are the IQR limits described above. Raw, tabulated data can be found in the Nuclear Data Management and Analysis System Database, including parameters specified by the applicable ASTM standard (e.g., dates, performer identifier, and laboratory conditions).

There are many ways to compare the data presented here. In doing so, the validity of the test data is exercised and scrutinized. First, the data sets are evaluated independently, using the statistical analysis described above. Additionally, a limited comparison of pre- and post-irradiation values is made for each graphite grade to show the effects of irradiation and applied stress (where applicable). Note that pre-irradiation properties were measured using the same techniques, equipment, and standards per the AGC-3 Graphite Specimen Pre-Irradiation Characterization Plan.[17] Pre-irradiation data for the AGC-3 specimens can be found in the AGC-3 Graphite Pre-Irradiation Data Analysis Report.[14] These initial comparisons provide an initial examination of the data for trends and correlations that are intuitive and logical. In this way, the physical and thermal post-irradiation property measurements are vetted.

The data presented in this report include testing from all irradiated AGC-3 graphite specimens. Variables of irradiation, grain orientation, and temperature are not considered for any property measurement in Figure 5 through Figure 9 or for the figures in appendix A. The data are presented simply to illustrate the measured material property trends for the major graphite grades in AGC-3. It should be noted that the averaged data shows significant spread across all material property measurements. This is expected since the data includes measurements from all samples and does not differentiate between the effects of irradiation dose, temperature variations, graphite grades, orientation, or the other factors being tested in the AGC Experiment. A more detailed analysis taking all test variables into consideration will be reported in the subsequent AGC-3 data analysis report(s).

4.1 Dimensions, Mass, and Density

Specimens are weighed and dimensionally measured at room temperature.[18] Plots of the measured dimensions, mass, and densities for all AGC-3 irradiated specimens are shown in Appendix A, Figure A-1 through Figure A-53. Prior to irradiation, the freshly machined surfaces produced consistent dimensional measurements with a COV of less than 0.05% for all specimens. Following irradiation, the surfaces are more irregular and inconsistent. This resulted in the creep specimens dimensional COVs increasing between 0.23 and 0.96% (see Appendix B, Table B-1 and Table B-2). Distributions in the pre- and post-irradiation mass data were similar with no difference in mass observed between pre- and post-irradiation measurements outside of the measurement uncertainty (see Appendix B, Table B-1).

Figure 5 shows the overall volume change for the irradiated specimens as a function of graphite grade and applied stress. Detailed volume dependency on irradiation dose and irradiation temperature will be addressed in the subsequent AGC-3 data analysis report. As expected, all graphite types experienced an overall shrinkage due to neutron irradiation. Shrinkage for all graphite types increased as the specimen stress increased. This is consistent with trends observed in the literature.[6,7]

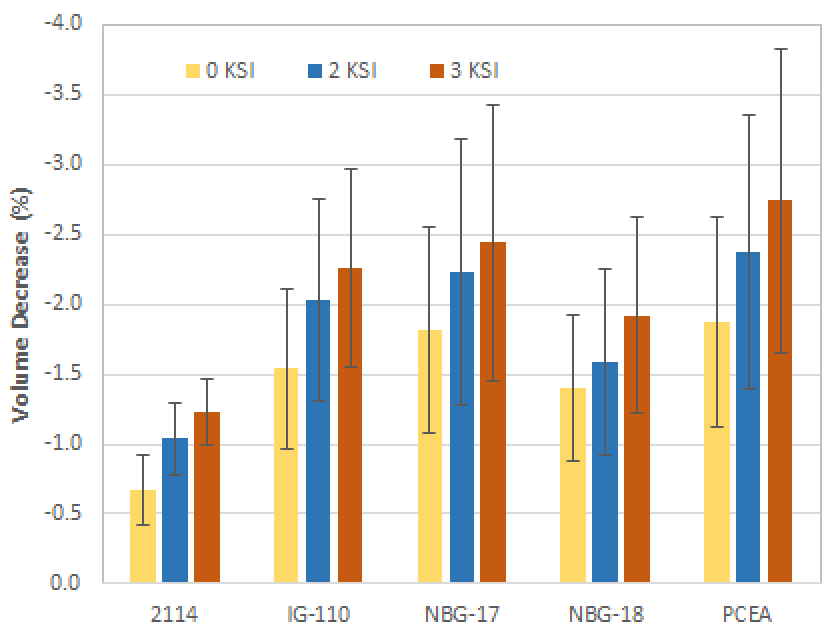

Figure 5. Volume decrease due to irradiation creep for five major grades of graphite.

Figure 6 shows an increase in density for all graphite grades that is a result of a reduction in volume with no change in mass. The greatest change in density occurs for the specimens that experience applied stresses. These specimens undergo a greater volume reduction while the unstressed condition results in less volume change from irradiation shrinkage only. The COV for density values of irradiated specimens of the individual graphite types was below 1.5% (see Appendix B, Table B-4). Detailed density analysis and trends will be addressed in the subsequent AGC-3 data analysis report.

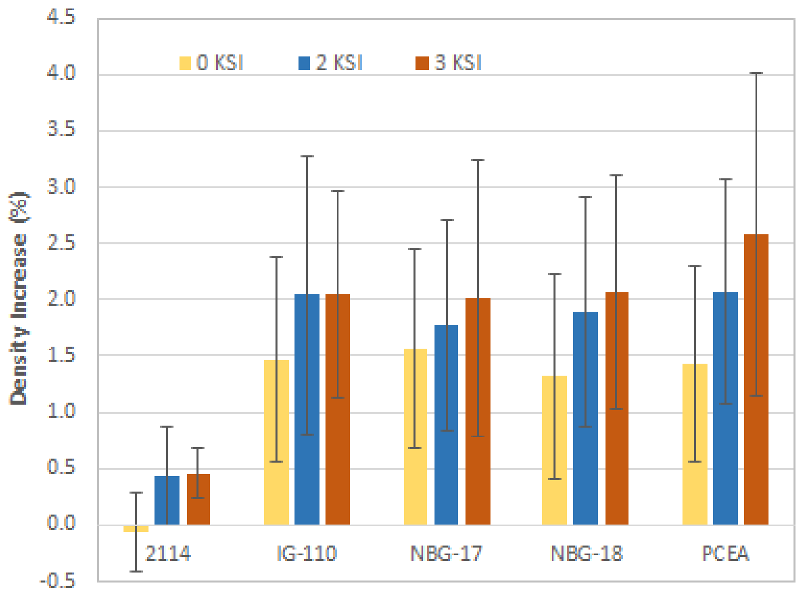

Figure 6. Density increase due to irradiation volume shrinkage for five major grades of graphite and three stress conditions. Error bars represent one standard deviation in the percent density increase.

4.2 Elastic Modulus

Elastic properties were measured with two dynamic nondestructive testing techniques at room temperature.[19,20,21,22] In the fundamental frequency testing technique, Young's modulus is derived from the natural frequency of the creep specimens oscilating in the flexural mode. Due to the geometry of the specimens, the shear modulus cannot be determined using this technique. However, both Young's modulus and shear modulus can be determined using the sonic velocity technique. In this case, an ultrasonic longitudinal or shear wave is sent through the specimen. The time it takes for this wave to pass through the specimen and the length of the specimen are used to determine the sonic velocity. Young's modulus and shear modulus can then be calculated from this time-of-flight measurement.

Young's modulus, determined by measurement of fundamental frequency, is plotted in Appendix A, Figure A-54 through Figure A-58, and the statistical data are contained in Appendix B, Table B-8. Statistically, these data are well-behaved, with the IQR analysis showing no significant outliers. Appendix A, Figure A-64 through Figure A-73, contain plots of Young's and shear moduli determined from the measurement of sonic velocity. Statistical parameters are shown in Appendix B, Table B-10 and Table B-11, for Young's and shear moduli, respectively, and again the IQR analysis does not reveal any inconsistency or significant outliers. The spread in all modulus data is reasonable with the COV approximately 5%.

It should be noted that for AGC-3 specimens, the dynamic Young's modulus values determined by sonic velocity testing techniques are generally 2 to 3 GPa higher than the measurements obtained by the fundamental frequency testing technique (Appendix A, Figure A-64 through Figure A-73). This difference between modulus measurements has been noted for a number of years and was finally addressed in the latest version of the sonic velocity standard (ASTM 769-09).[19] In this latest ASTM standard version, the Young's modulus value is calculated from the time-of-flight measurement using a correction factor designated as the Poisson's factor (C_v), which is normally valued at 0.9. Calculating the modulus using the Poisson's factor effectively lowers the value by 10%, bringing the measured sonic velocity values to values arrived at by the fundamental frequency test method.

However, AGC-3 pre-irradiation testing was performed under the previous ASTM sonic velocity standard, ASTM 769-98 (reapproved 2005),[20] which does not use the Poisson's factor to calculate the modulus values. The AGC-3 characterization plan (PLN-4888) specifies that the testing standards used to measure the material properties for the graphite specimens must be the same version before and after irradiation.[18] Using the same ASTM test method version assures the unirradiated and irradiated measurements will be consistent and comparable without testing method bias.

Since only the measured data is being corrected by the Poisson's factor, and not the actual testing technique itself, the pre- and post-irradiation AGC-3 sonic velocity data can be recalculated. Recalculating the data will be considered in the subsequent AGC-3 data analysis report to provide a more accurate modulus value from the sonic velocity testing method.

While the absolute Young's modulus values between sonic velocity and fundamental frequency may be different for the AGC-3 measurements, when making relative comparisons between pre- and post-irradiation measurements, the difference is consistent between the two techniques. Dynamic Young's modulus generally increases when pre- and post-irradiation Young's modulus values (as a percentage) are compared. This increase is shown to be similar for the fundamental frequency and sonic velocity testing techniques (see Figure 7 and Figure 8). Detailed Young's modulus dependency on irradiation dose and irradiation temperature will be addressed in the subsequent AGC-3 data analysis report.

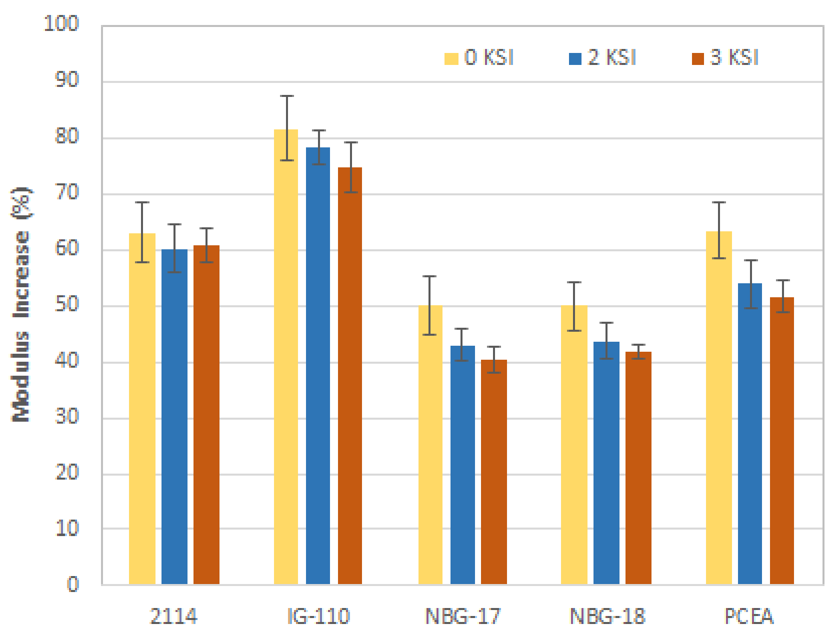

Figure 7. Young's modulus derived from the measurement of fundamental frequency for five grades of graphite and three different stress conditions.

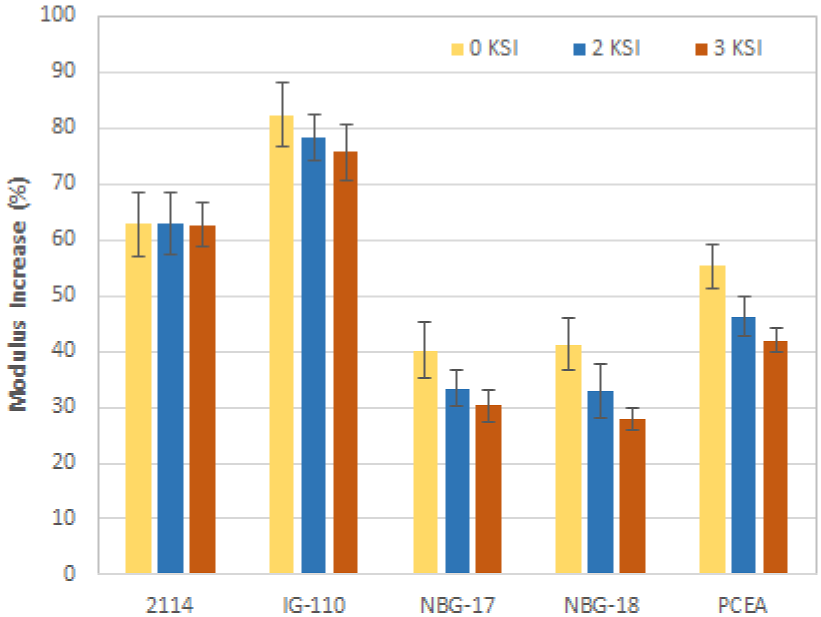

Figure 8. Young's modulus derived from the measurement of ultrasonic velocity for five grades of graphite and three different stress conditions.

4.3 Resistivity

Plots of electrical resistivity are shown in Appendix A, Figure A-59 through Figure A-63, for graphite grades of 2114, IG-110, NBG-17, NBG-18, and PCEA. Resistivity measurements were performed on the longer creep specimens only.[18] Statistical parameters can be found in Appendix B, Table B-9. The resistivity data are well behaved with only one 2114 specimen outlier and one PCEA specimen outlier. A closer look at the resistance measurements showed that these specimens had consistent, but either high or low resistance values. Since these measurements were stable, the final resistivity values are included in the data. Overall, the COV of the resistivity measurements ranged from 2.3 to 3.6%.

Specimen resistivity is measured at room temperature using a four-point testing method. A constant current is passed through the long axis of the specimen, and the voltage is measured at a fixed distance along the specimen axis. Resistivity is calculated from these values and the specimen geometry. Figure 9 shows the percent increase of the specimens' resistivity. Detailed electrical resistivity analysis, including irradiation dose and irradiation temperature effects, will be addressed in the subsequent AGC-3 data analysis report.

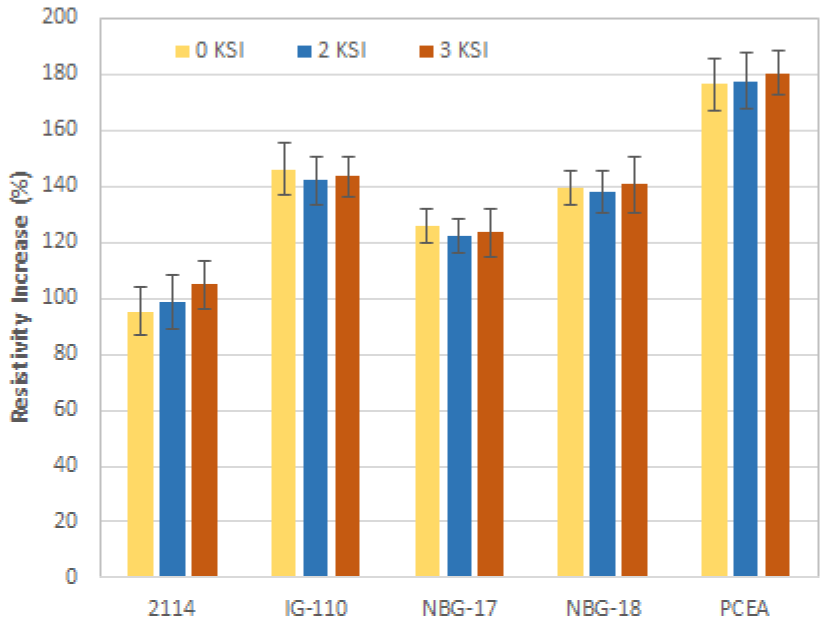

Figure 9. Electrical resistivity for five grades of graphite and three different stress conditions.

4.4 Thermal Diffusivity

Thermal diffusivity was measured using a laser flash technique.[18] Because annealing of irradiation damage begins to take place at temperatures above the irradiation temperature, measurements of thermal diffusivity were limited to 650°C (about 170°C below the average AGC-3 specimen irradiation temperature).

Plots of thermal diffusivity are shown in Appendix A, Figure A-89 through Figure A-112. Discrete temperatures of 100, 400, and 650°C were statistically evaluated. Appendix B, Table B-16 through Table B-18, contain values of the mean, standard deviation, and COV. Considering the complexities associated with measuring the thermal diffusivity of irradiated specimens, the COVs are reasonable, ranging between approximately 1% and approximately 12%. There were however, four specimens (three 2114 and one NBG-18) that fell outside of the IQR limits (see Appendix A, Figure A-89, Figure A-93, Figure A-97, Figure A-101, Figure A-105, and Figure A-109). The data from these outliers were consistently higher across all of the measurement temperatures than the other specimens within their same grade. In order to validate the measurements of these outliers, they were re-measured and compared with their initial measurements. The results were virtually the same. Therefore, there is no reason, at this time, to suspect that the initial measurements are incorrect and these data outside the IQR limits are maintained with the complete data set.

Figure 10 shows the average diffusivity of all specimens of a particular type of graphite over the measurement temperature range. The plot shows that the greatest change in diffusivity occurs at the lower measurement temperatures. All graphite grades follow this similar trend. Detailed diffusivity dependency analysis, including irradiation dose and irradiation temperature dependency, will be addressed in the subsequent AGC-3 data analysis report.

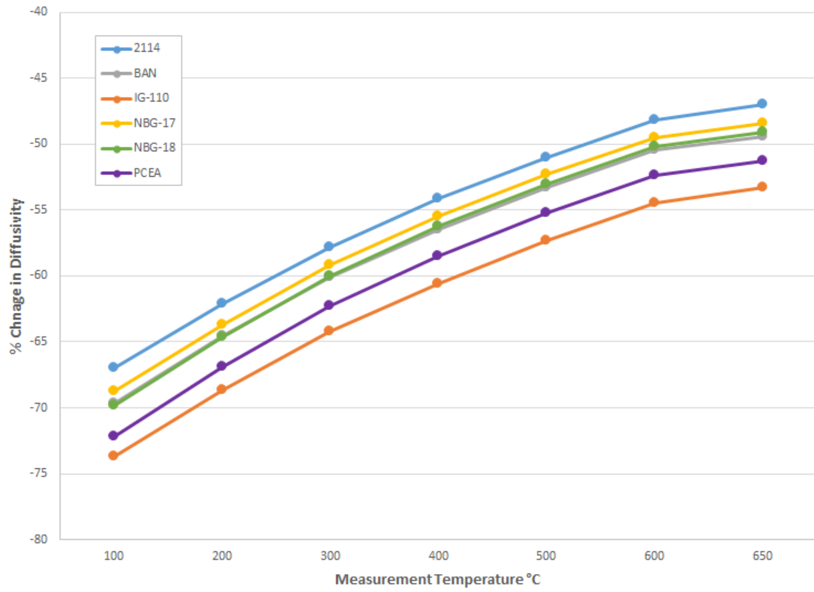

Figure 10. Percent change in diffusivity as a function of measurement temperature for six grades of graphite.

4.5 Coefficient of Thermal Expansion

CTE was measured using a linear dilatometer technique.[18] Because annealing of irradiation damage begins to take place at temperatures above the irradiation temperature, measurements of thermal expansion were limited to 650°C (about 170°C below the average AGC-3 specimen irradiation temperature).

Mean CTE data are plotted in Appendix A, Figure A-74 through Figure A-88. A statistical evaluation of the CTE data was performed at three discrete temperatures (i.e., 100, 400, and 650°C) for each graphite type. Again, the dashed lines in these plots indicate the upper and lower IQR limits. There are no outliers to consider.

Appendix B, Table B-5 through Table B-7, list the mean, standard deviation, and COV values for data evaluated at the discrete temperatures. As shown, COV values range from approximately 8 to 12%. This is a relatively large scatter to the data and will be evaluated further in the subsequent AGC-3 data analysis report.

Figure 11 shows the average change in CTE as a function of the measurement temperature for stressed and unstressed specimens of the five major graphite grades. Each data point is averaged over all specimen doses and irradiation temperatures for each graphite grade. Specimens that were mechanically loaded are averaged over stress values of 2 and 3 ksi. The measured CTE values for all stressed creep specimens (the dashed lines) are considerably higher than the unstressed control specimens of the same grade and will be analyzed further in the subsequent AGC-3 data analysis report.

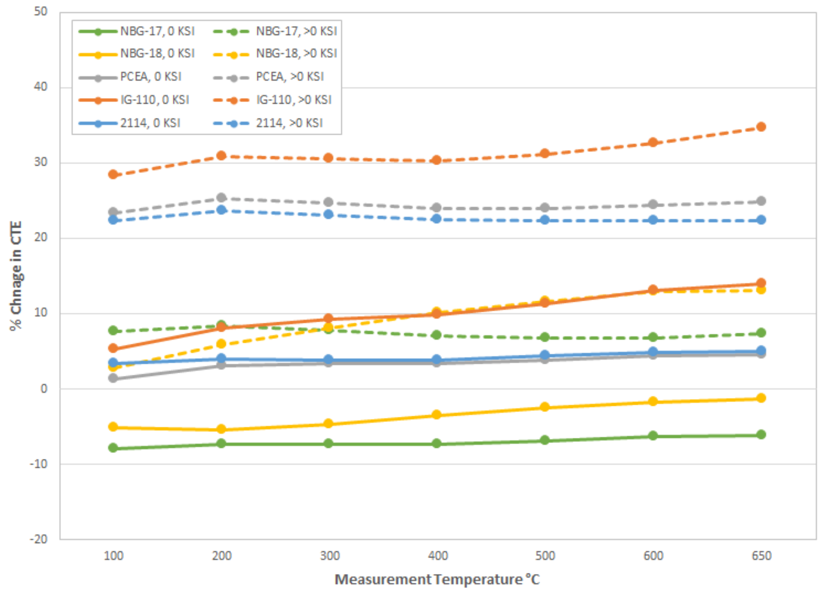

Figure 11. Percent change in CTE for six different grades of graphite as a function of temperature for stressed and unstressed conditions.

5. REFERENCES

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Appendix A

Data Plots

Appendix A

Data Plots

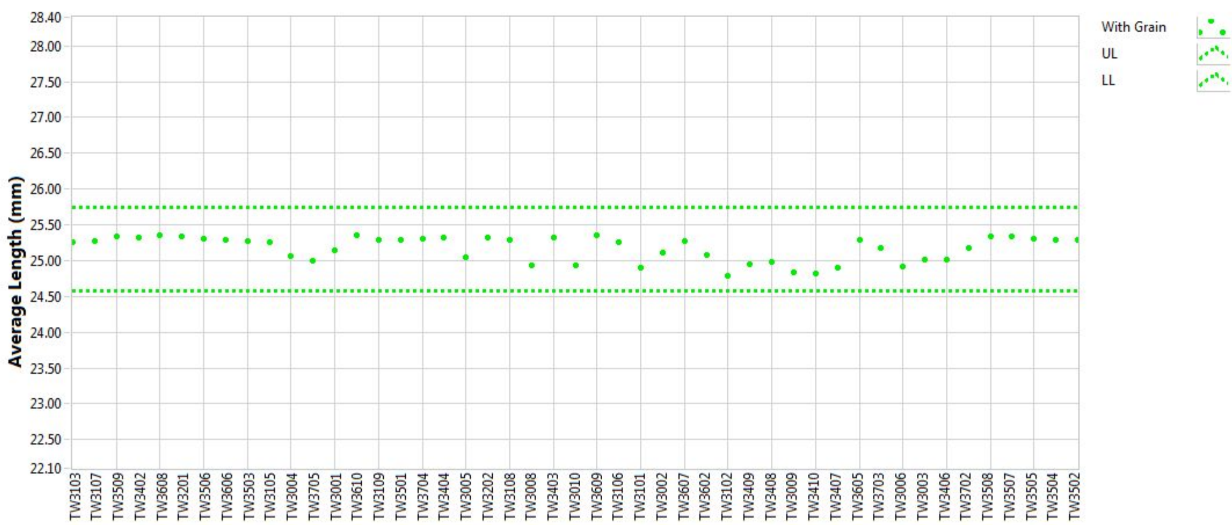

Figure A-1. 2114 creep length.

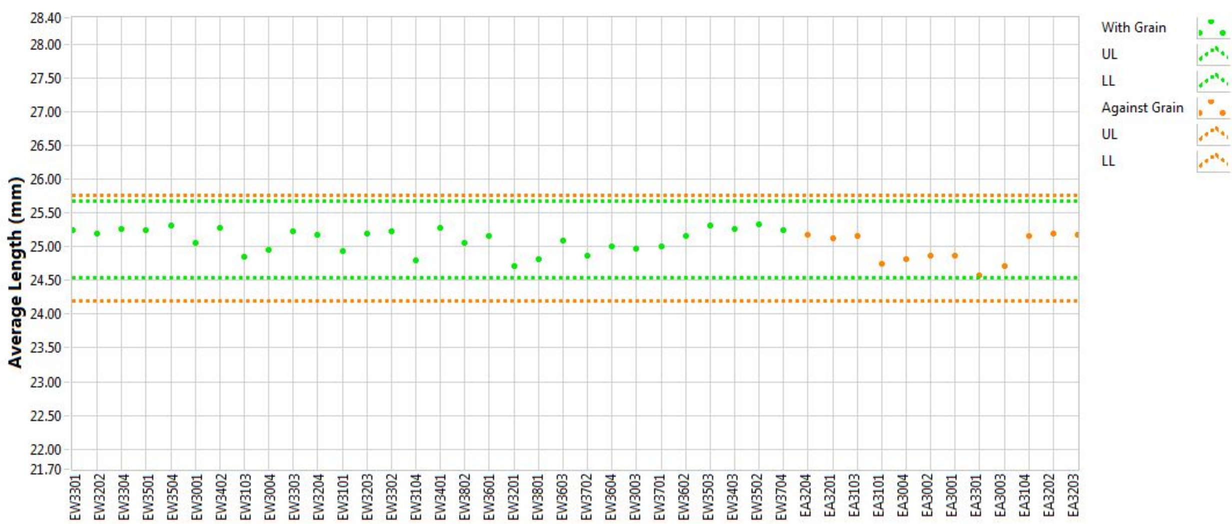

Figure A-2. IG-110 creep length.

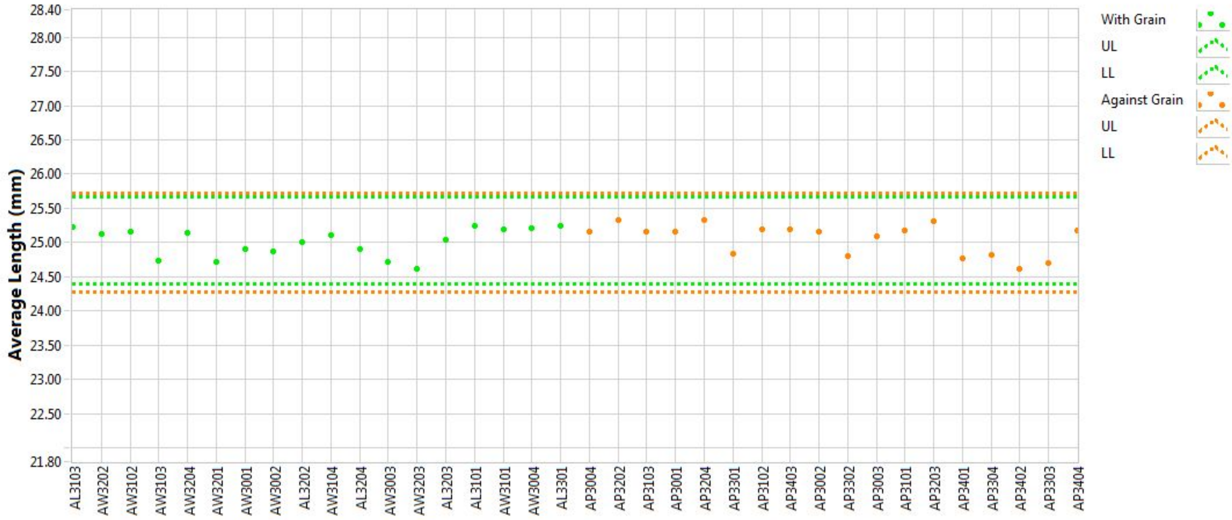

Figure A-3. NBG-17 creep length.

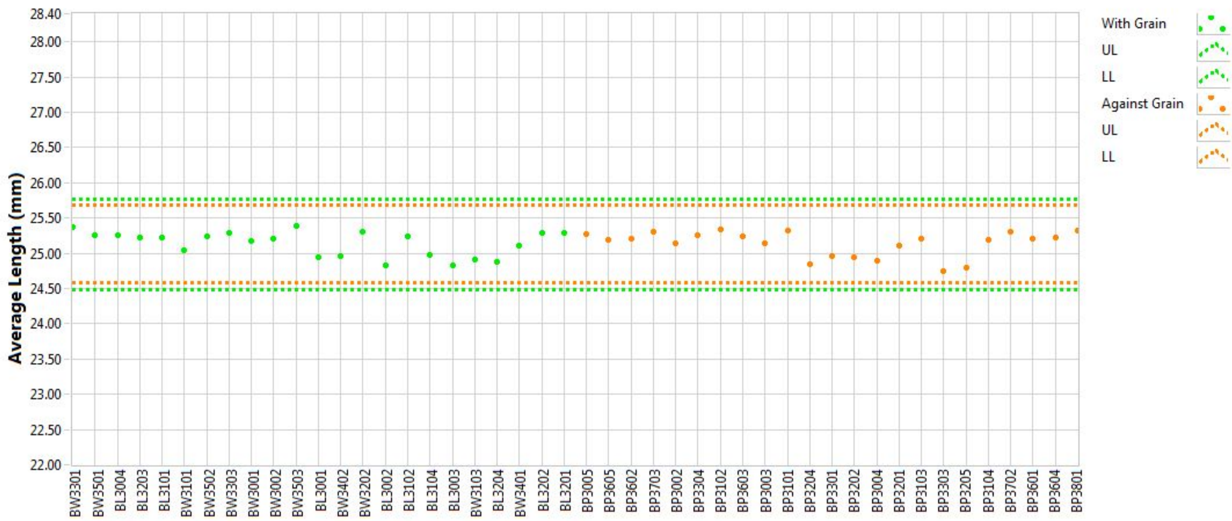

Figure A-4. NBG-18 creep length.

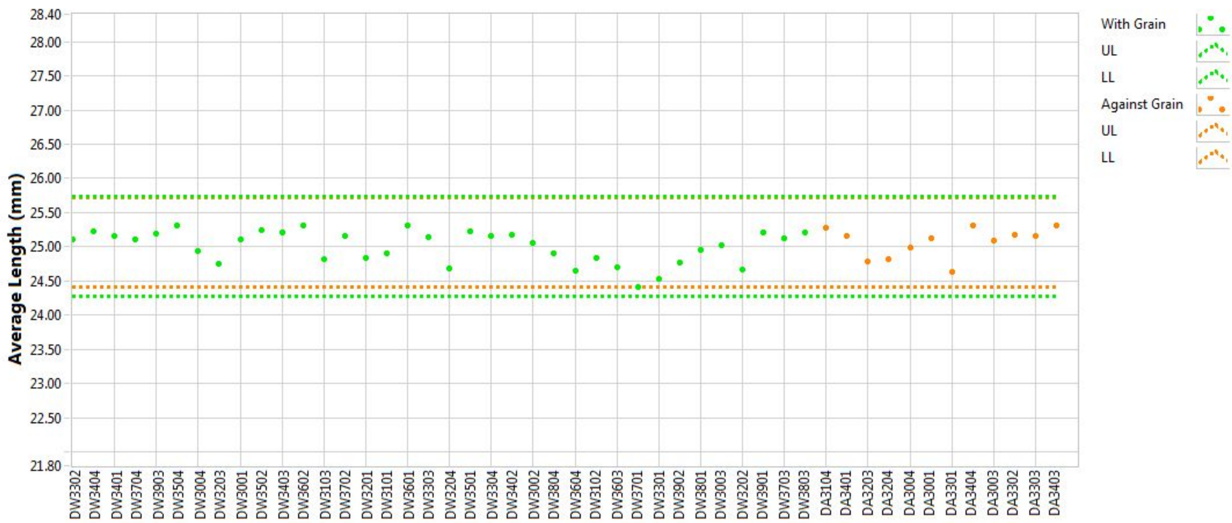

Figure A-5. PCEA creep length.

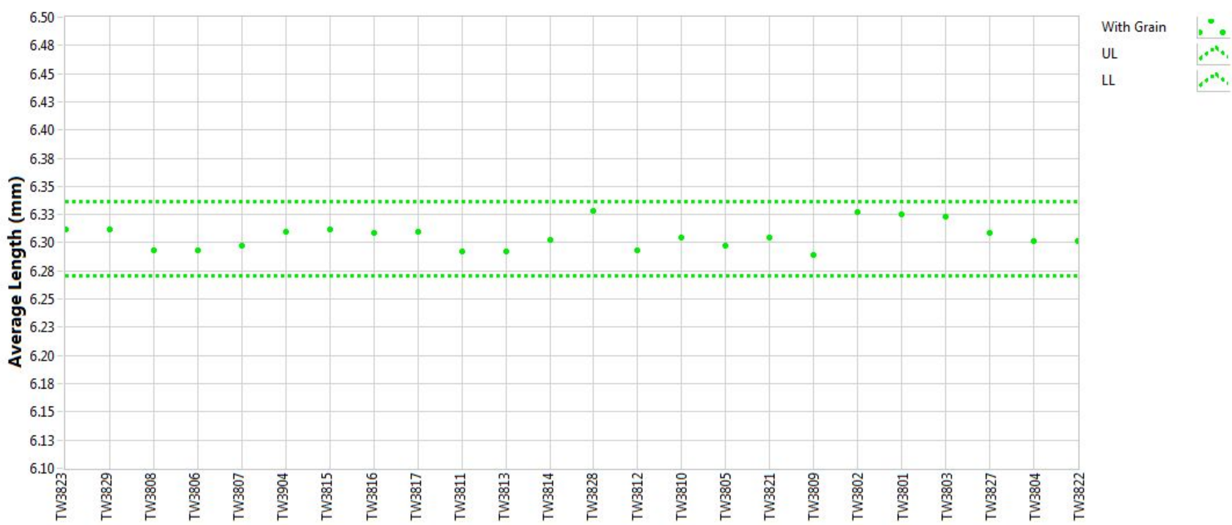

Figure A-6. 2114 piggyback length.

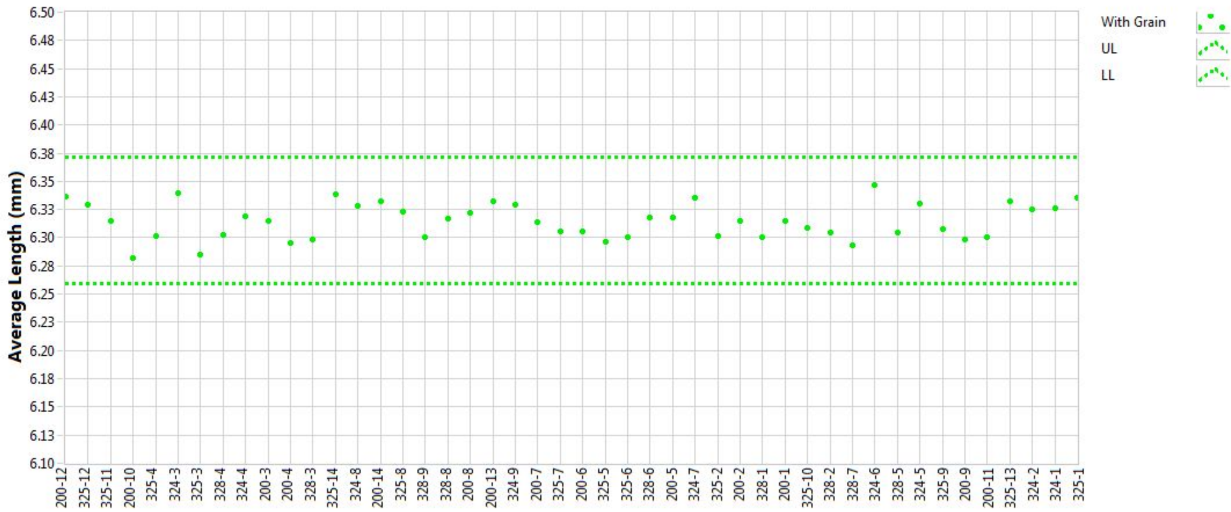

Figure A-7. GrafTech piggyback length.

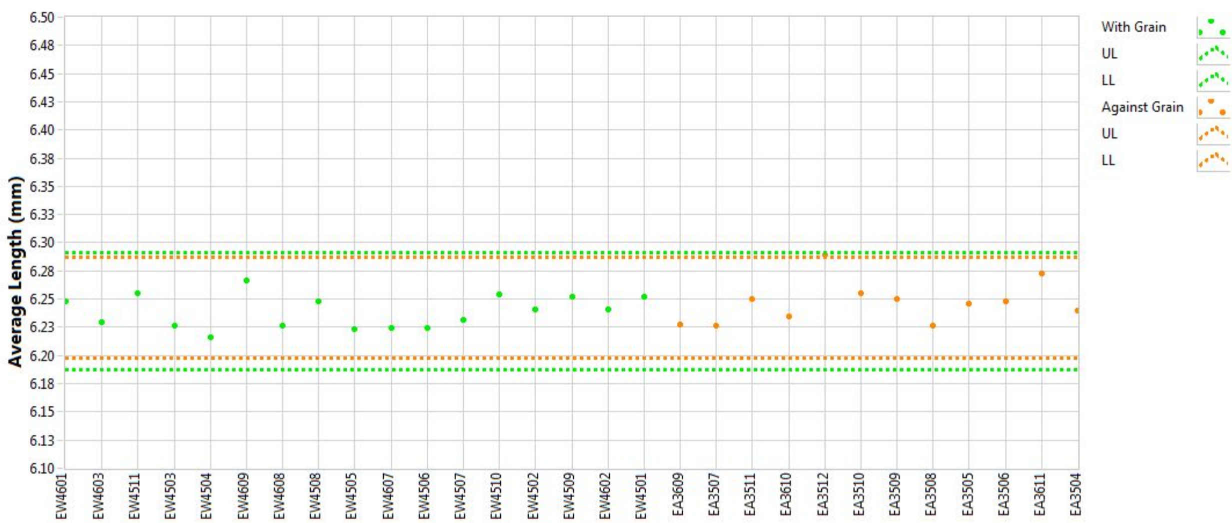

Figure A-8. IG-110 piggyback length.

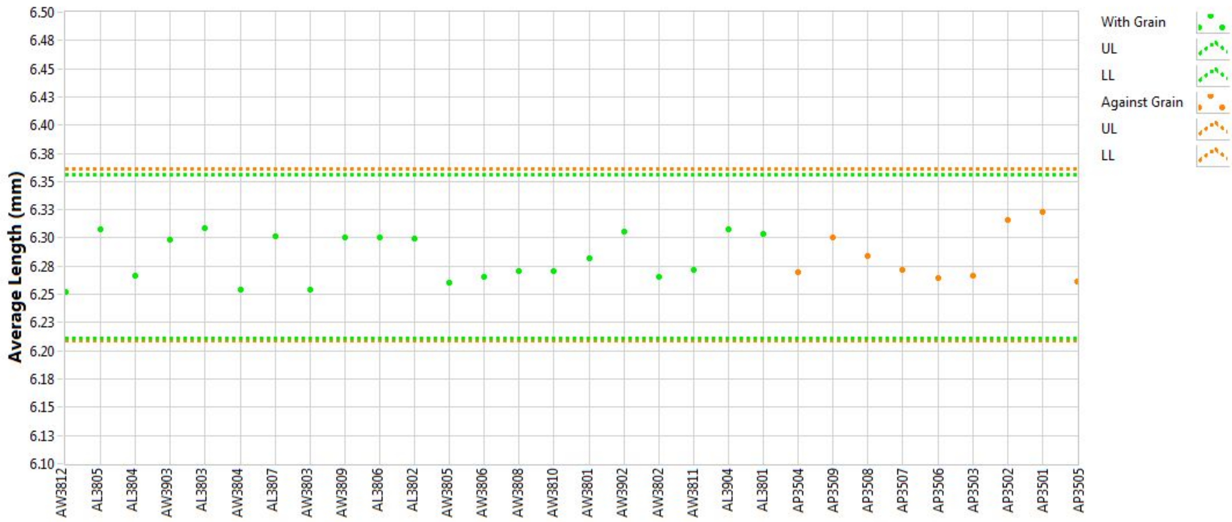

Figure A-9. NBG-17 piggyback length.

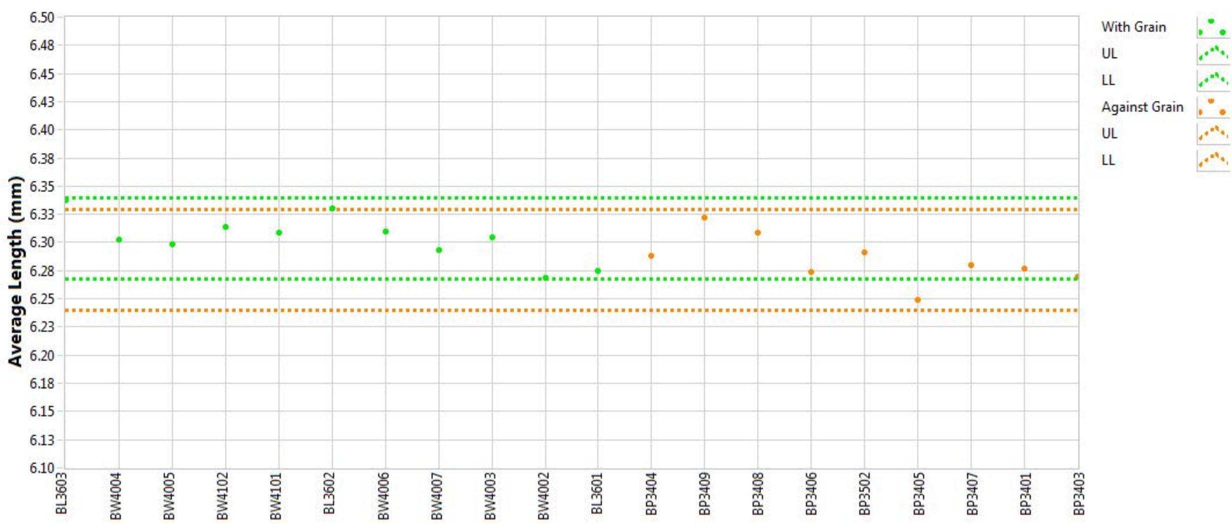

Figure A-10. NBG-18 piggyback length.

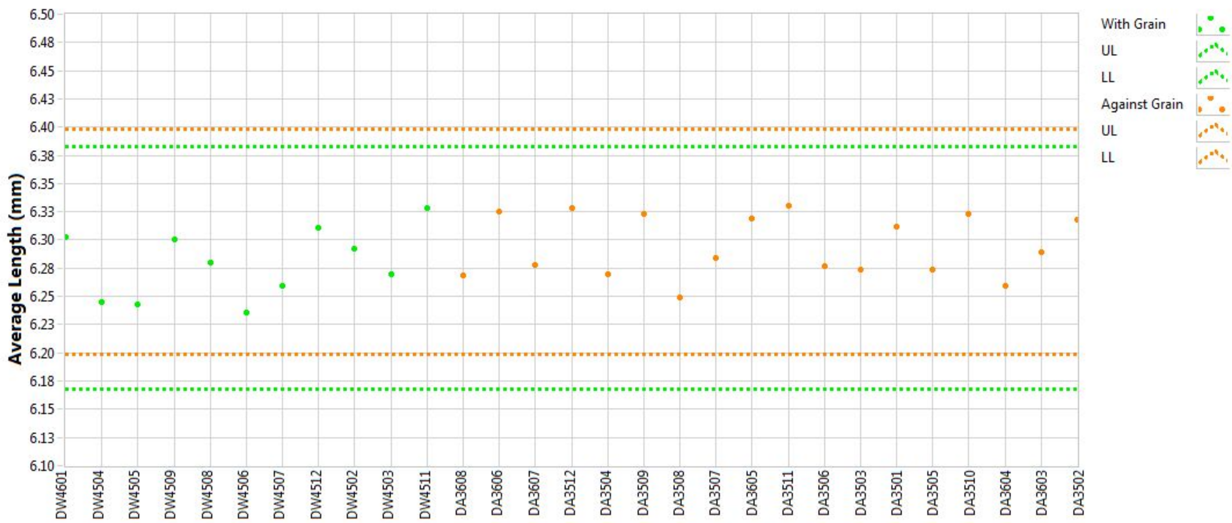

Figure A-11. PCEA piggyback length.

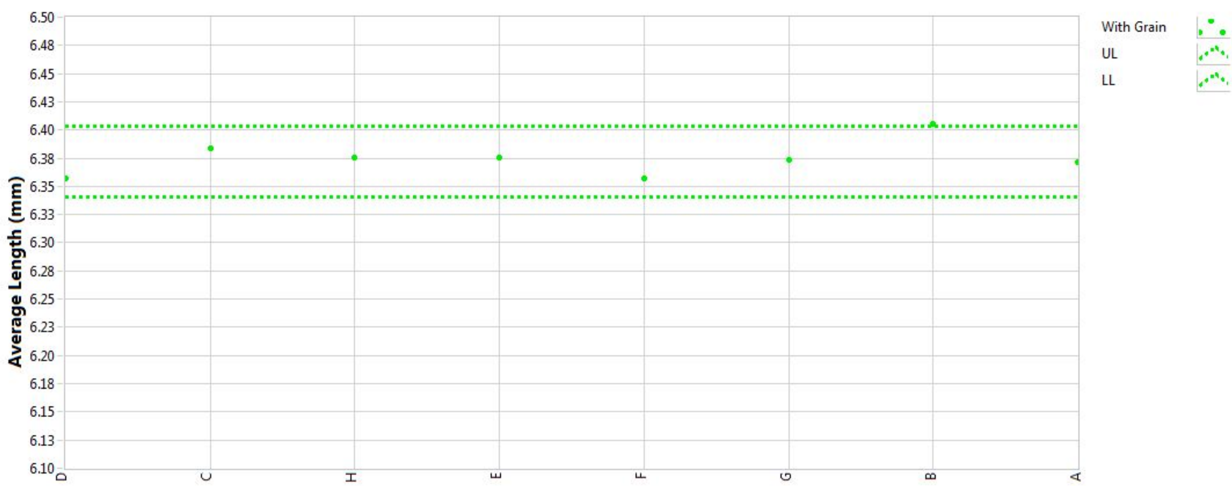

Figure A-12. SGL-SiC piggyback length.

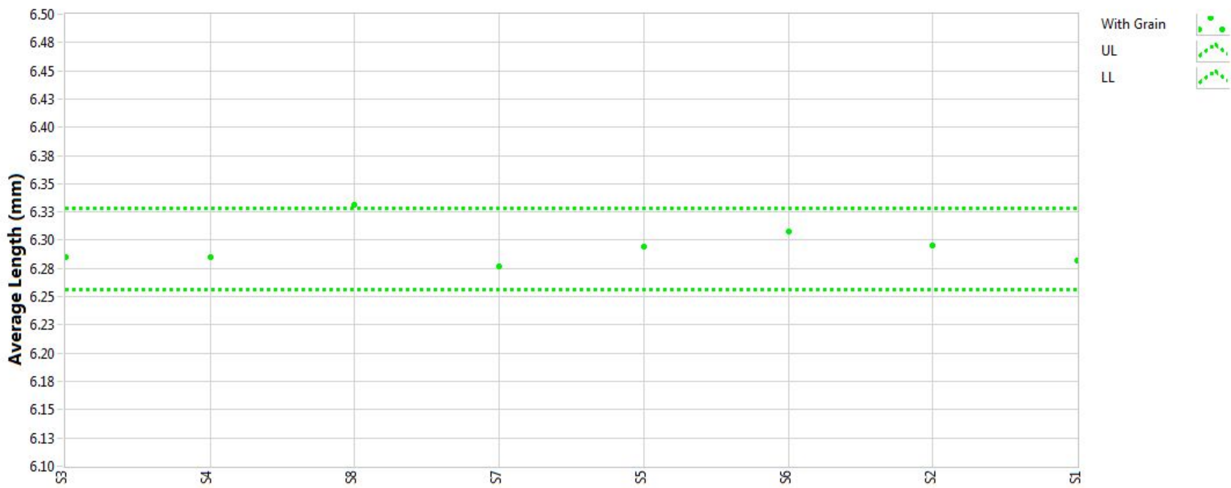

Figure A-13. SGL piggyback length.

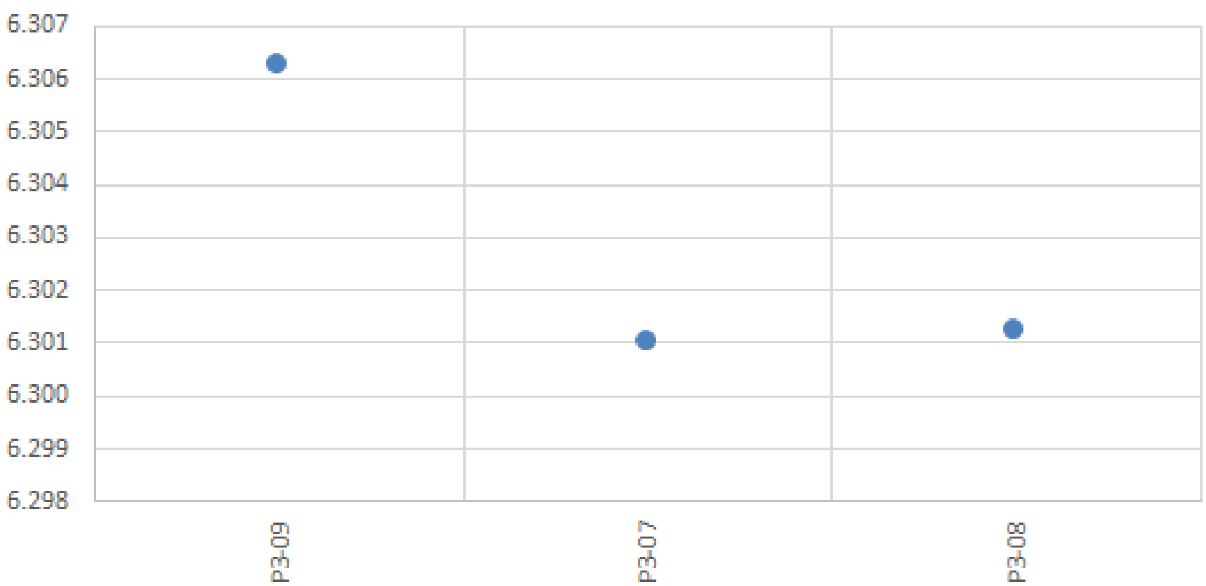

Figure A-14. PCIB piggyback length.

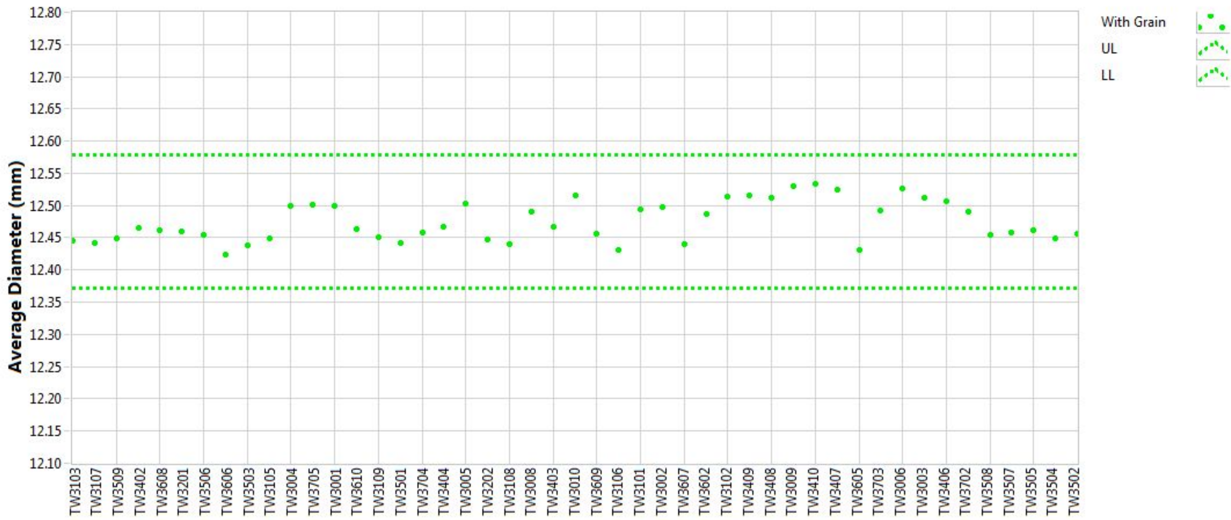

Figure A-15. 2114 creep diameter.

Figure A-16. IG-110 creep diameter.

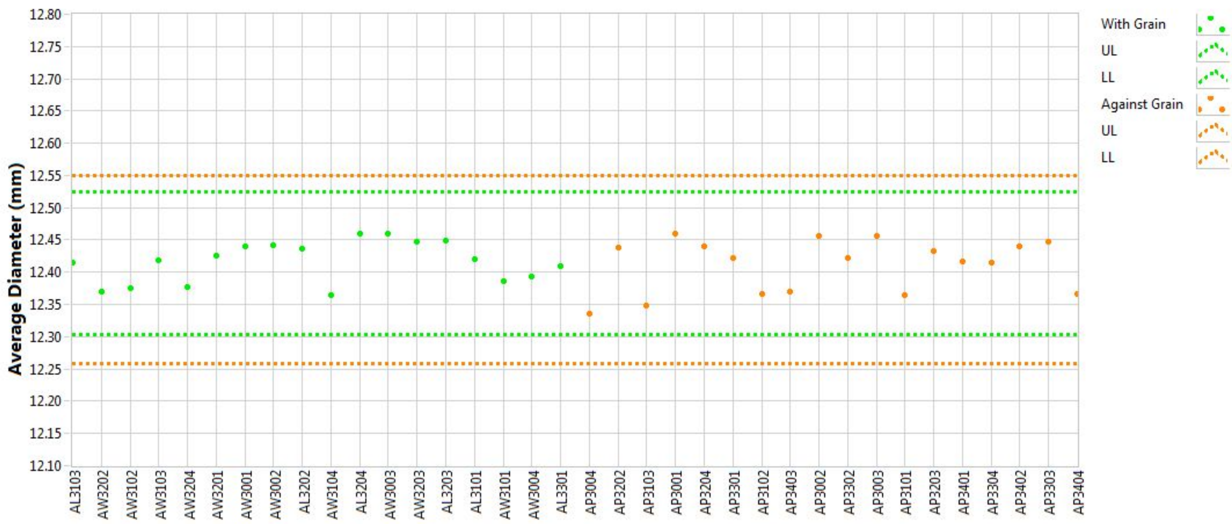

Figure A-17. NBG-17 creep diameter.

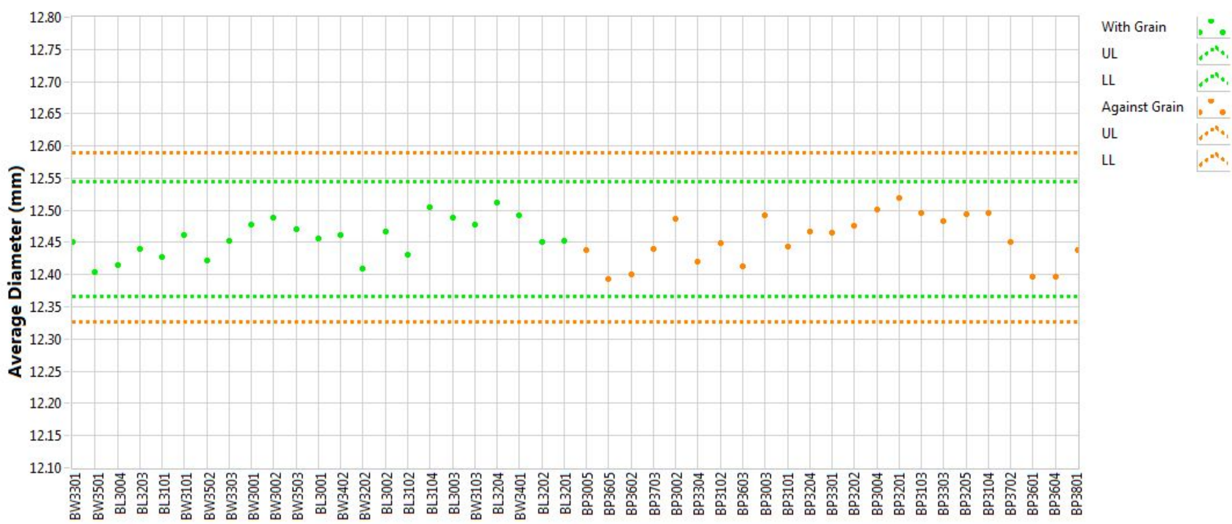

Figure A-18. NBG-18 creep diameter.

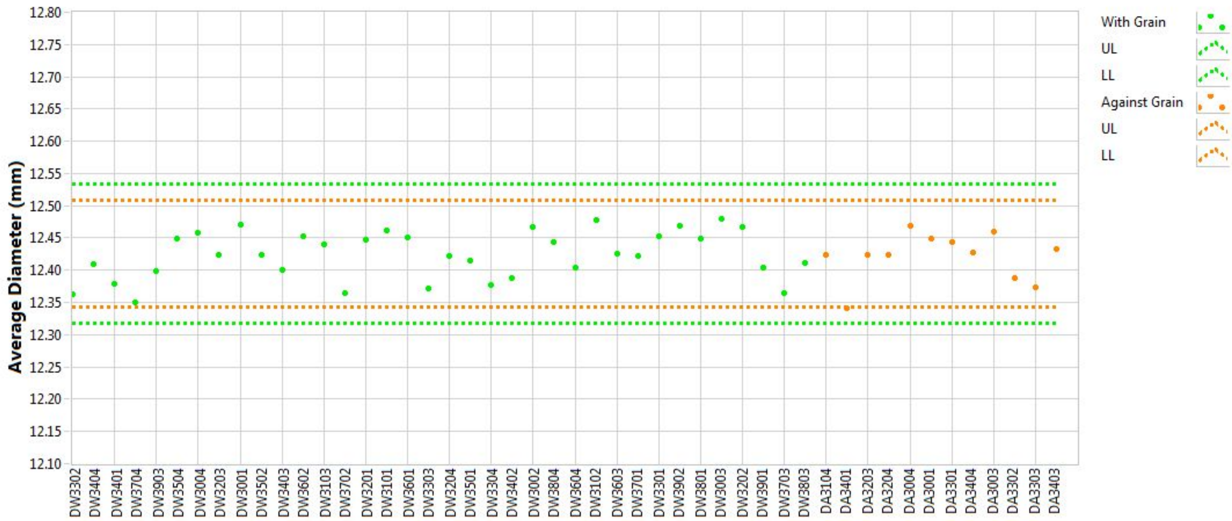

Figure A-19. PCEA creep diameter.

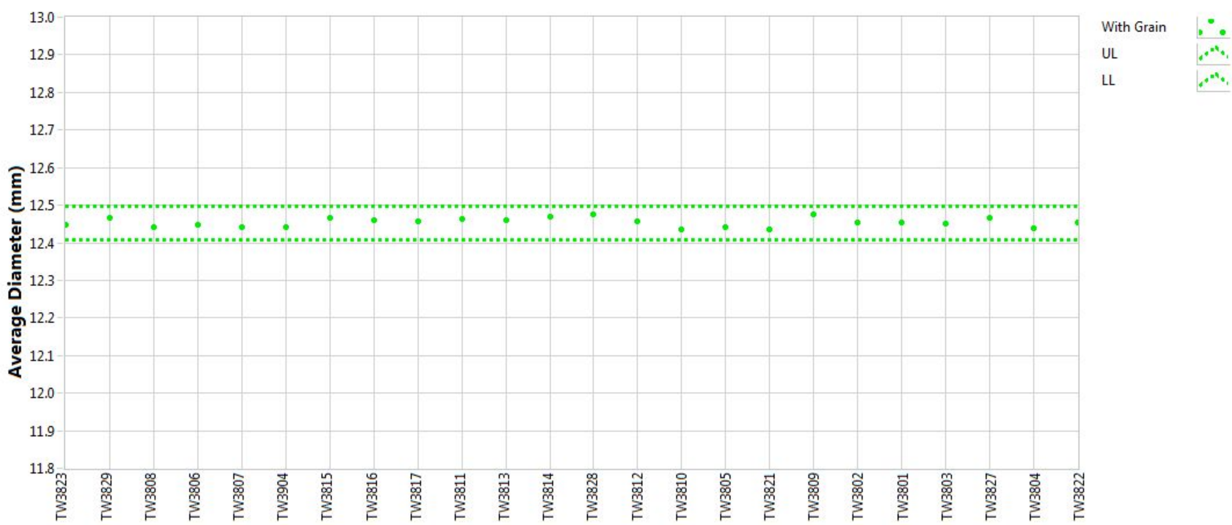

Figure A-20. 2114 piggyback diameter.

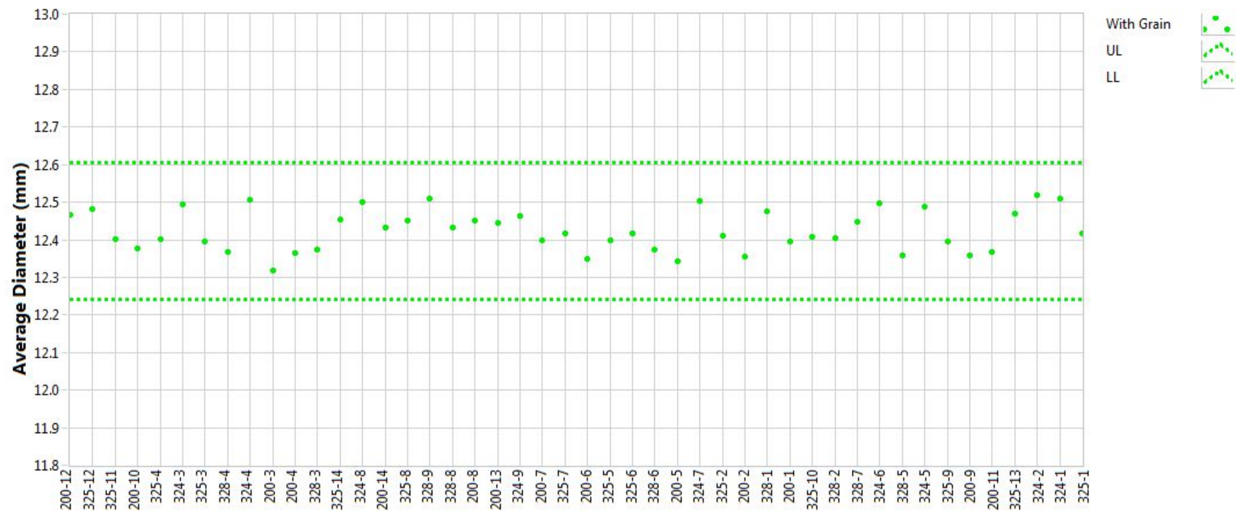

Figure A-21. GrafTech piggyback diameter.

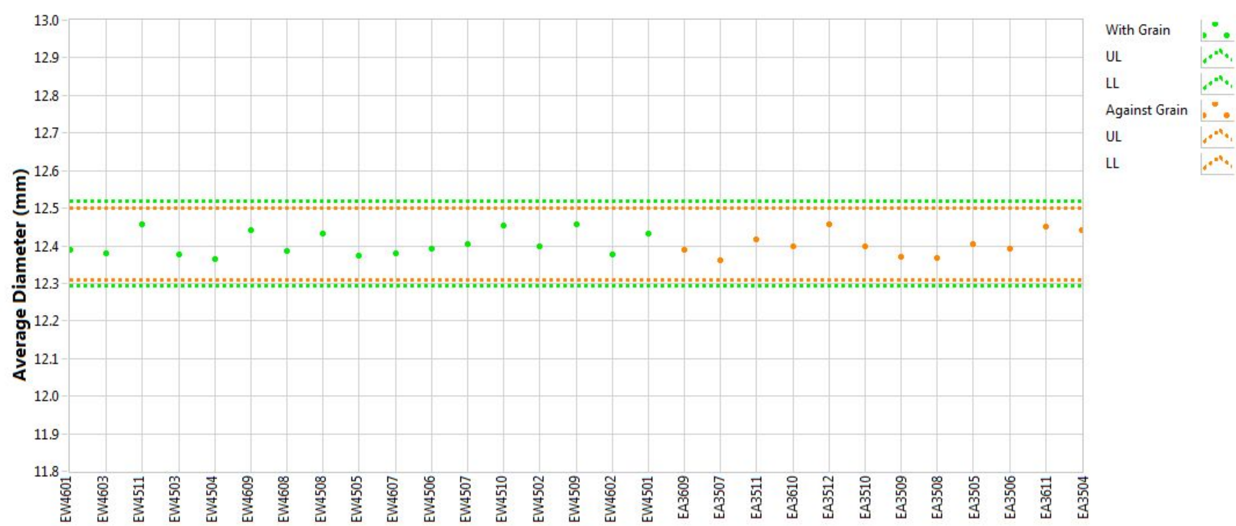

Figure A-22. IG-110 piggyback diameter.

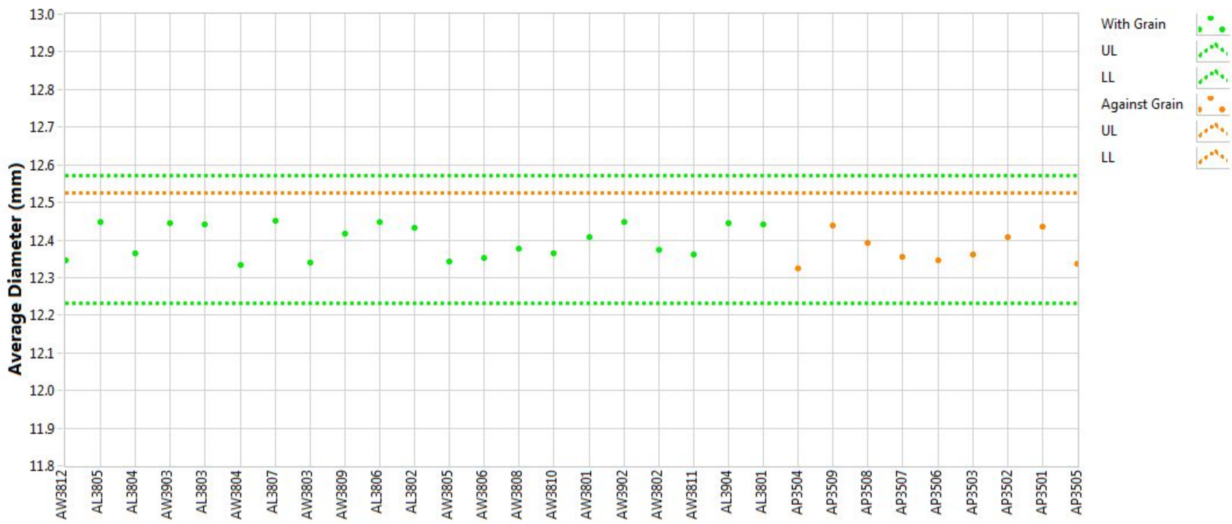

Figure A-23. NBG-17 piggyback diameter.

Figure A-24. NBG-18 piggyback diameter.

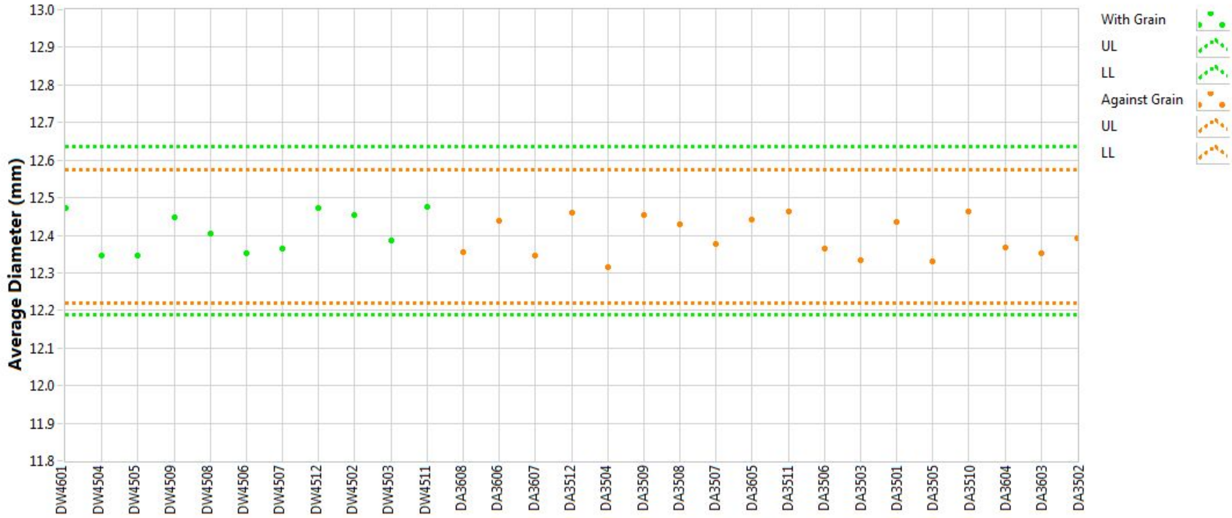

Figure A-25. PCEA piggyback diameter.

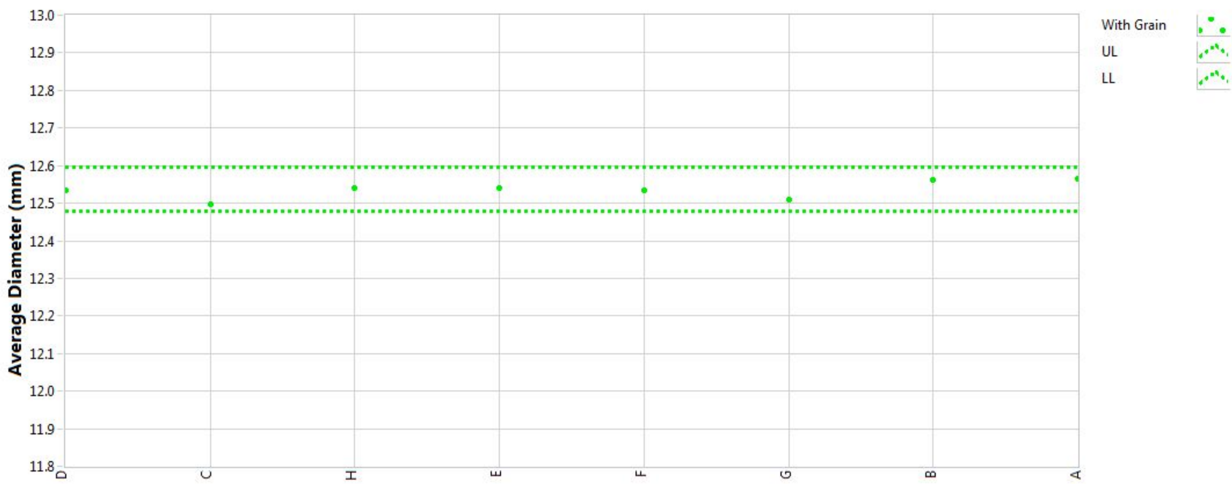

Figure A-26. SGL-SiC piggyback diameter.

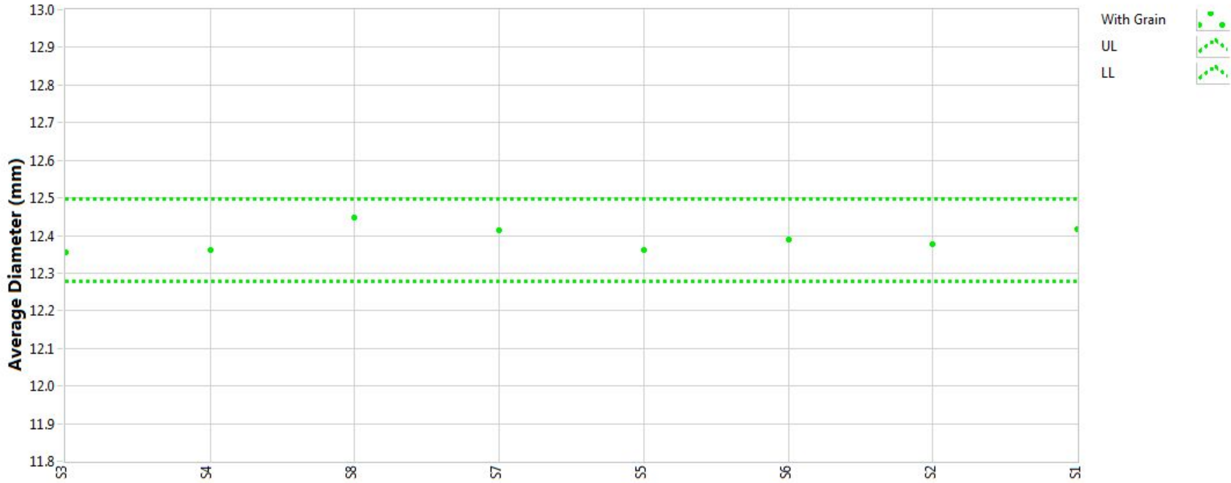

Figure A-27. SGL piggyback diameter.

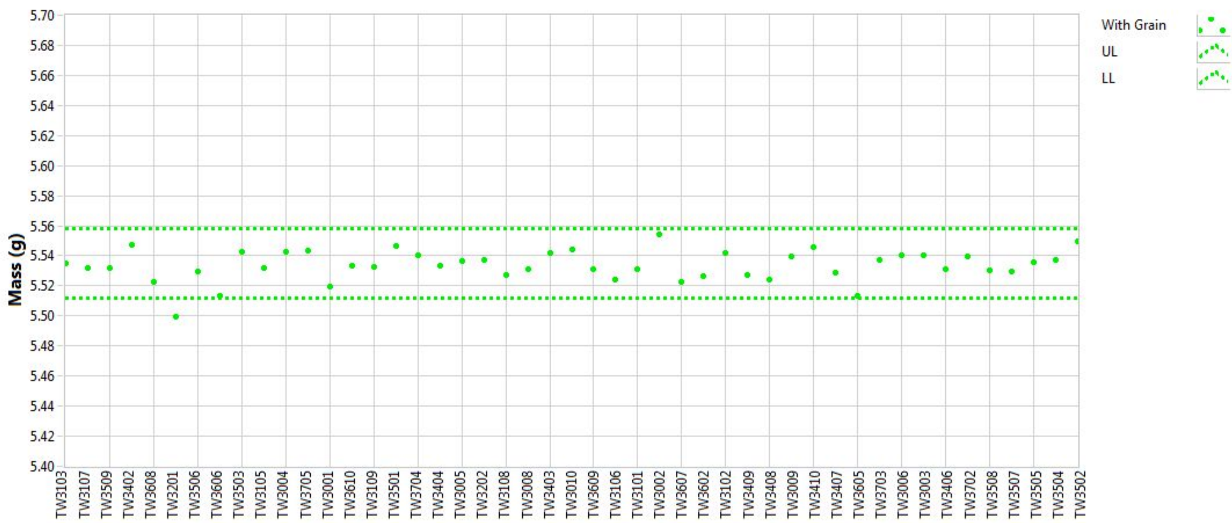

Figure A-28. 2114 creep mass.

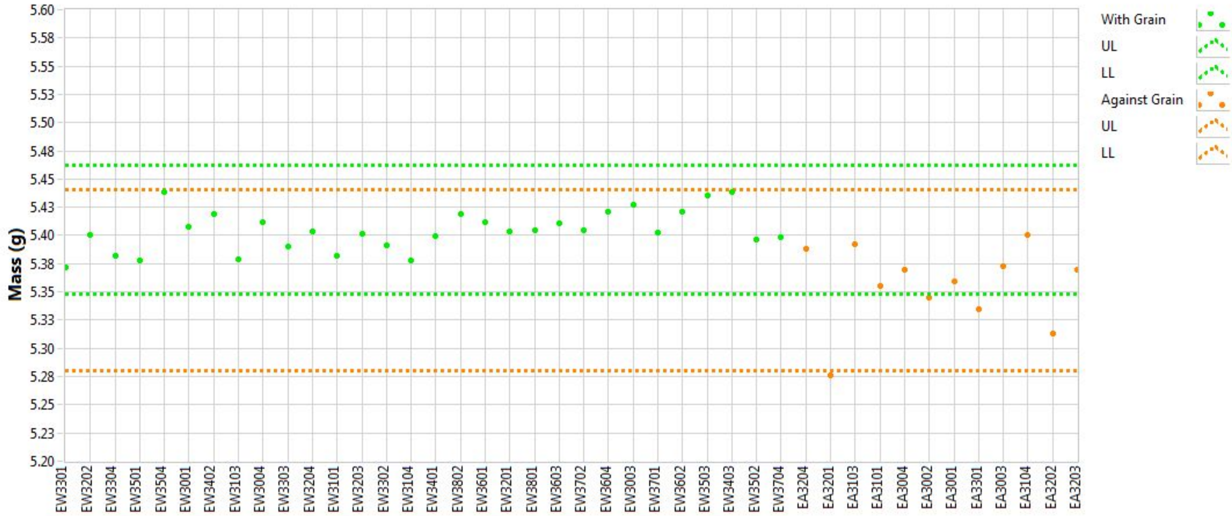

Figure A-29. IG-110 creep mass.

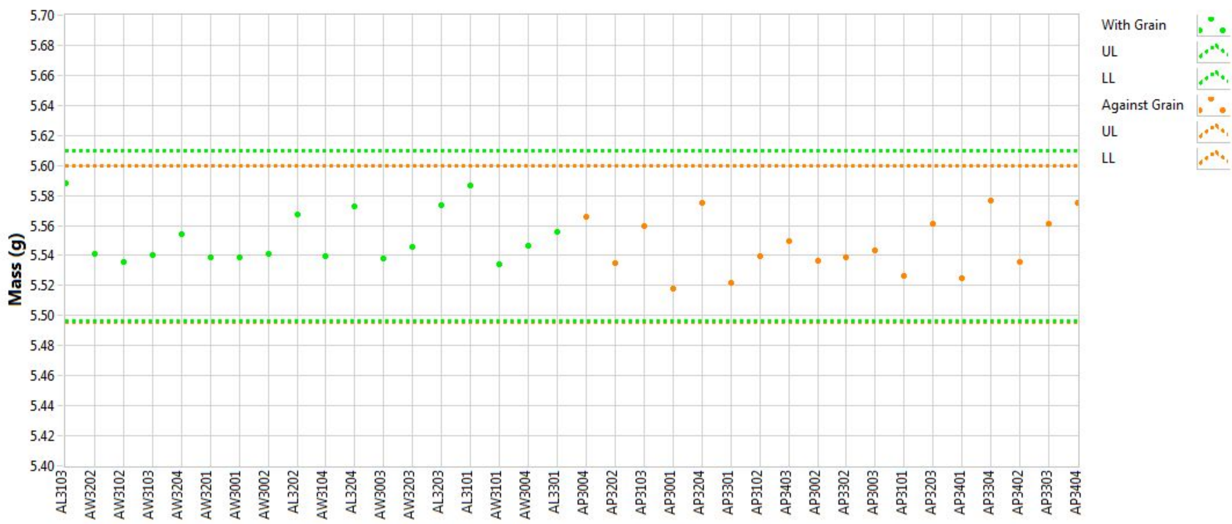

Figure A-30. NBG-17 creep mass.

Figure A-31. NBG-18 creep mass.

Figure A-32. PCEA creep mass.

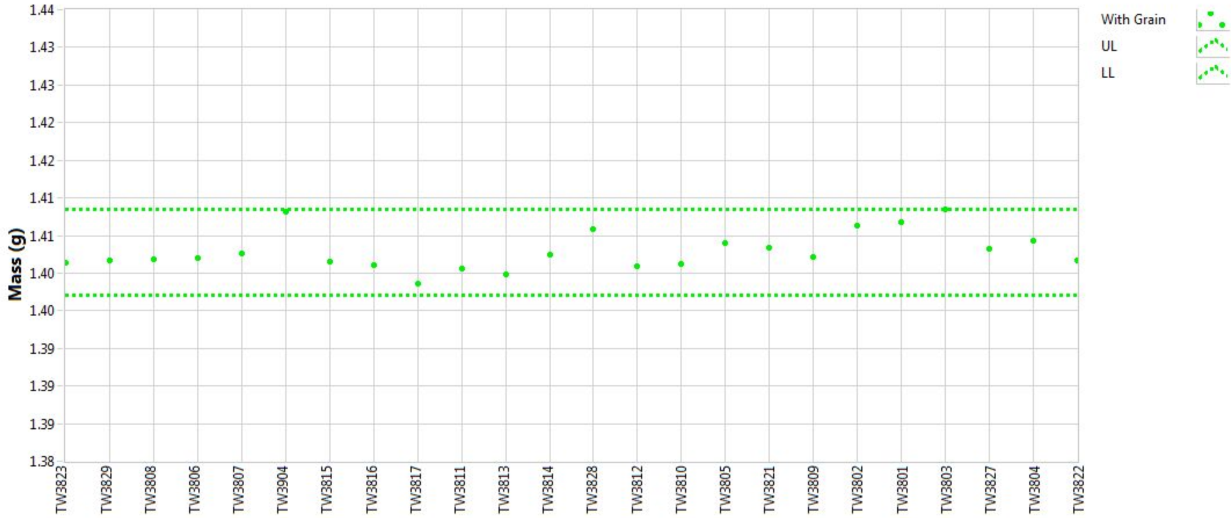

Figure A-33. 2114 piggyback mass.

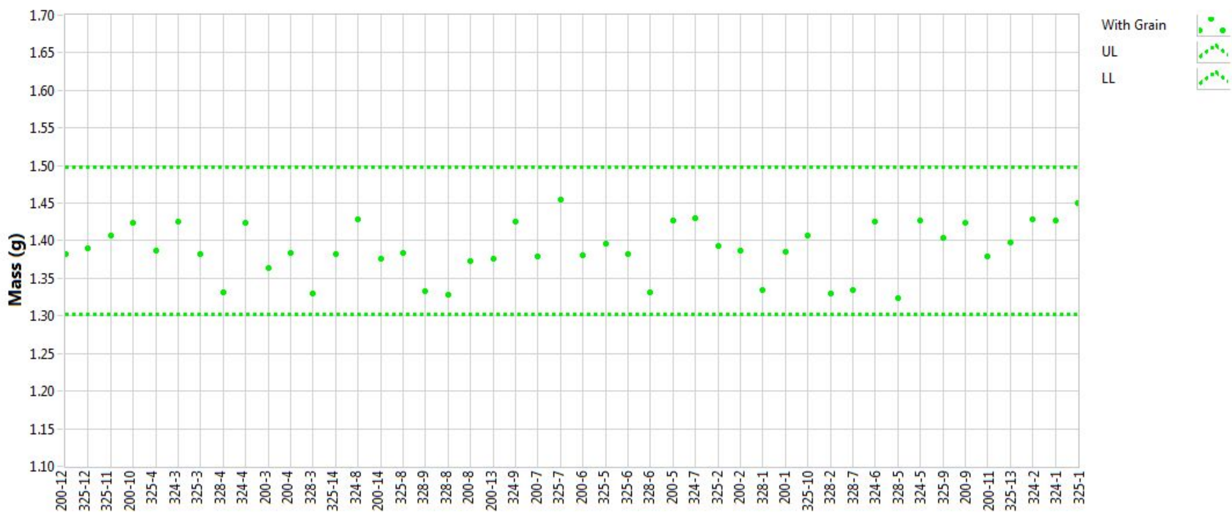

Figure A-34. GrafTech piggyback mass.

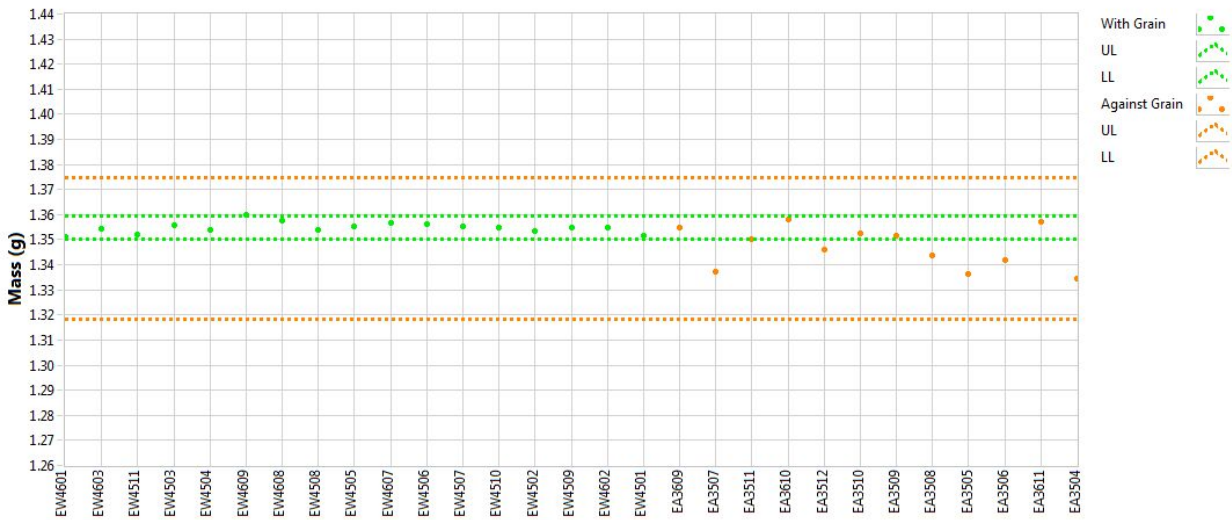

Figure A-35. IG-110 piggyback mass.

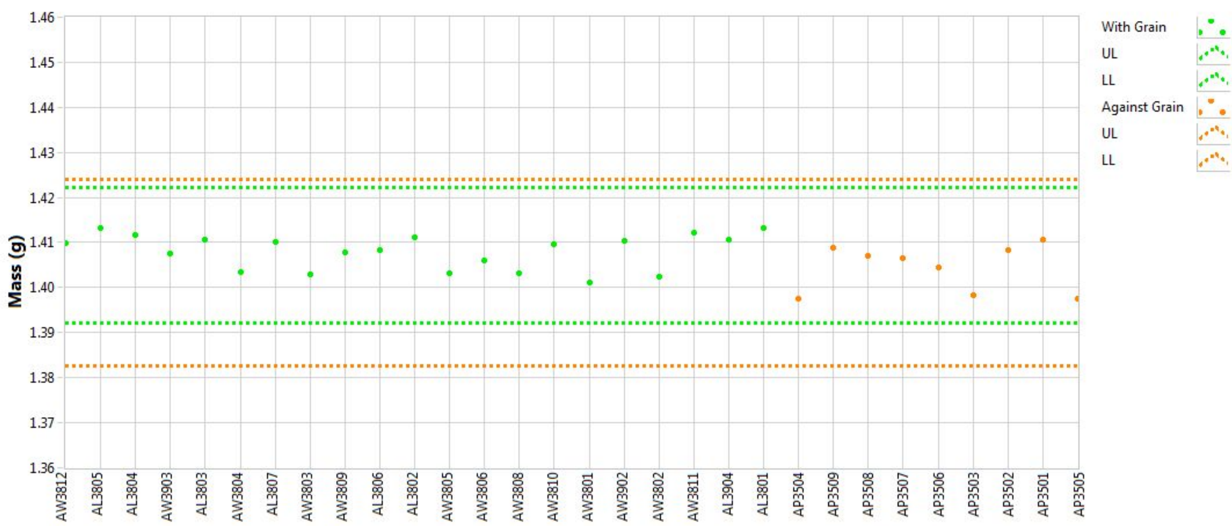

Figure A-36. NBG-17 piggyback mass.

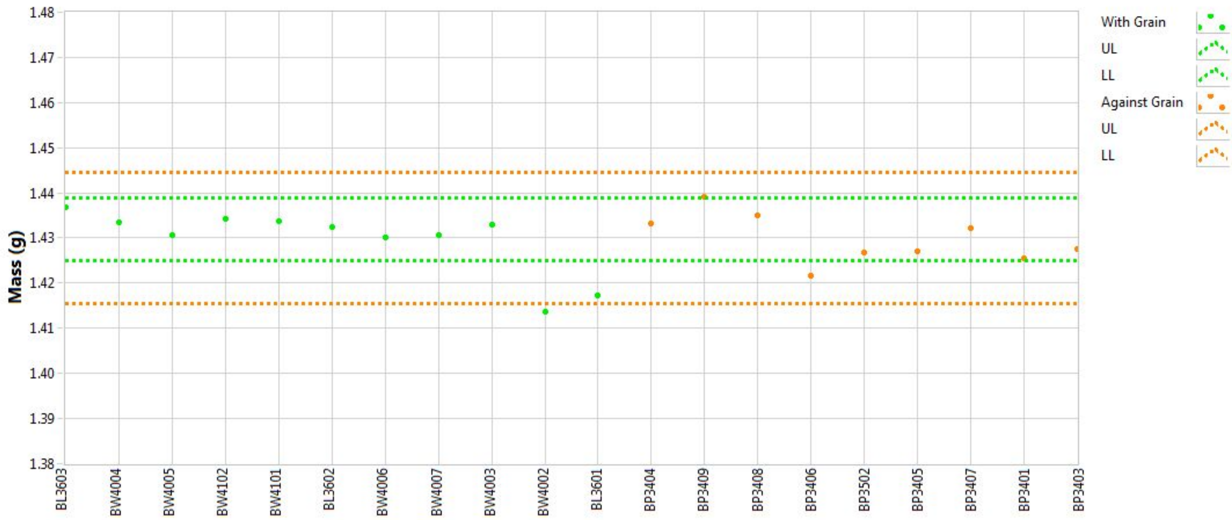

Figure A-37. NBG-18 piggyback mass.

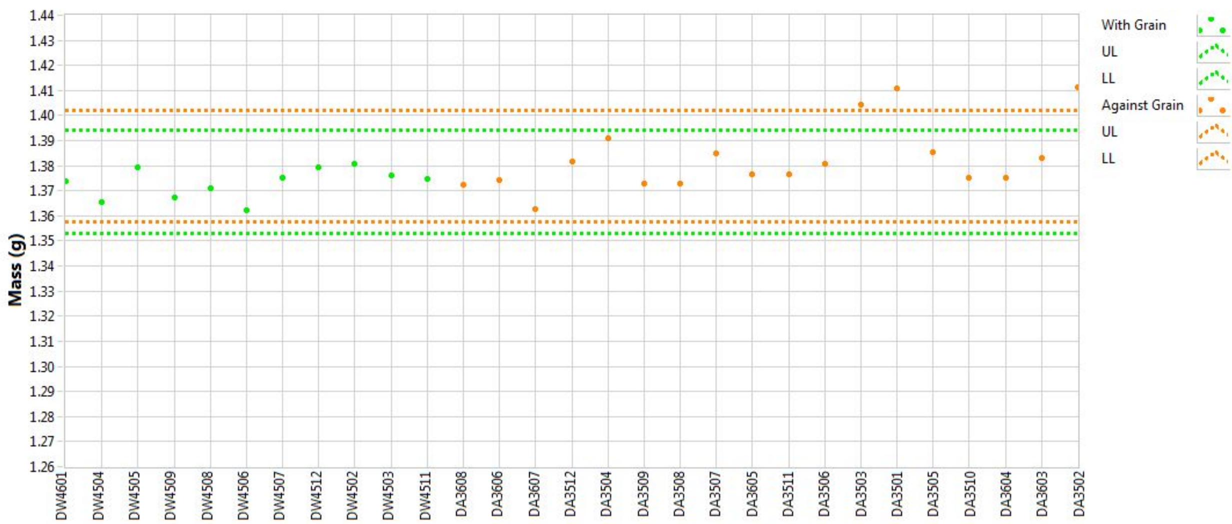

Figure A-38. PCEA piggyback mass.

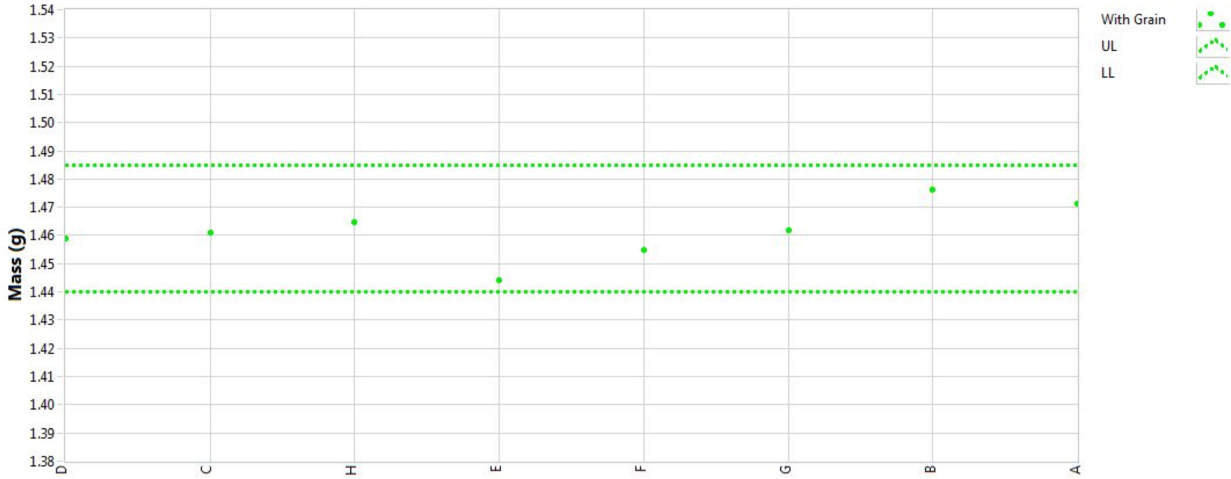

Figure A-39. SGL-SiC piggyback mass.

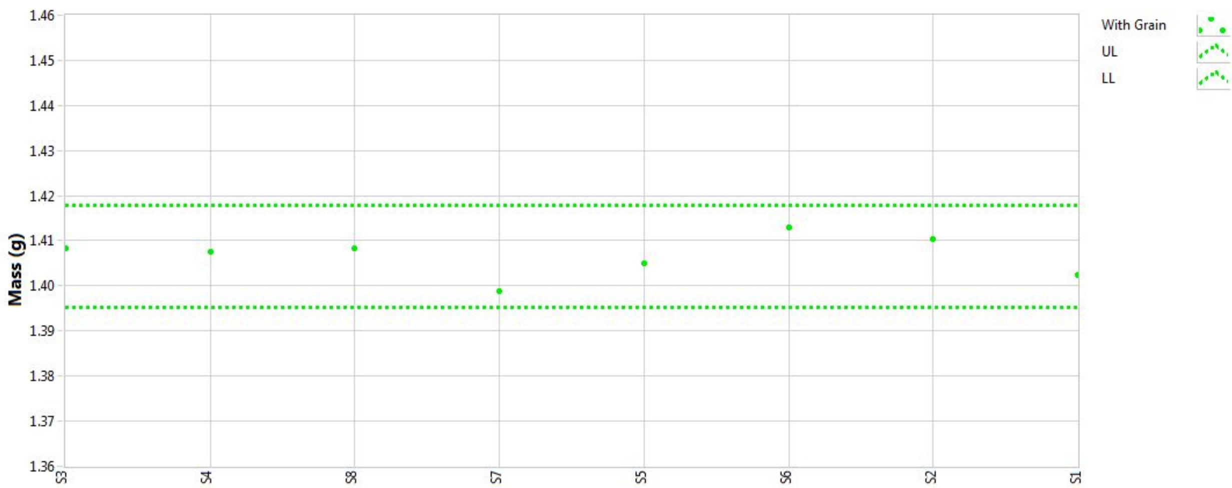

Figure A-40. SGL piggyback mass.

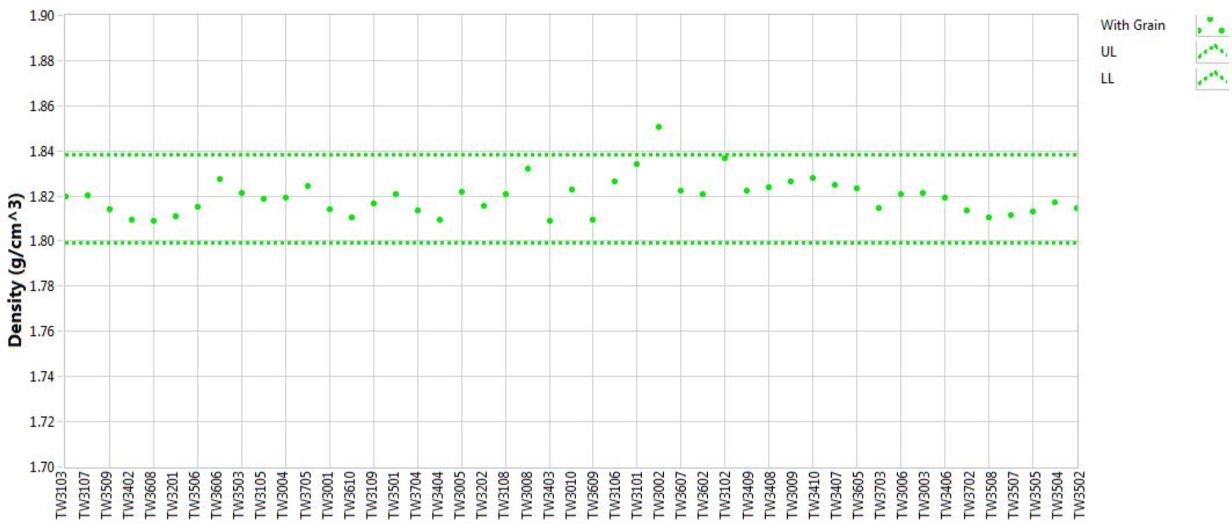

Figure A-41. 2114 creep density.

Figure A-42. IG-110 creep density.

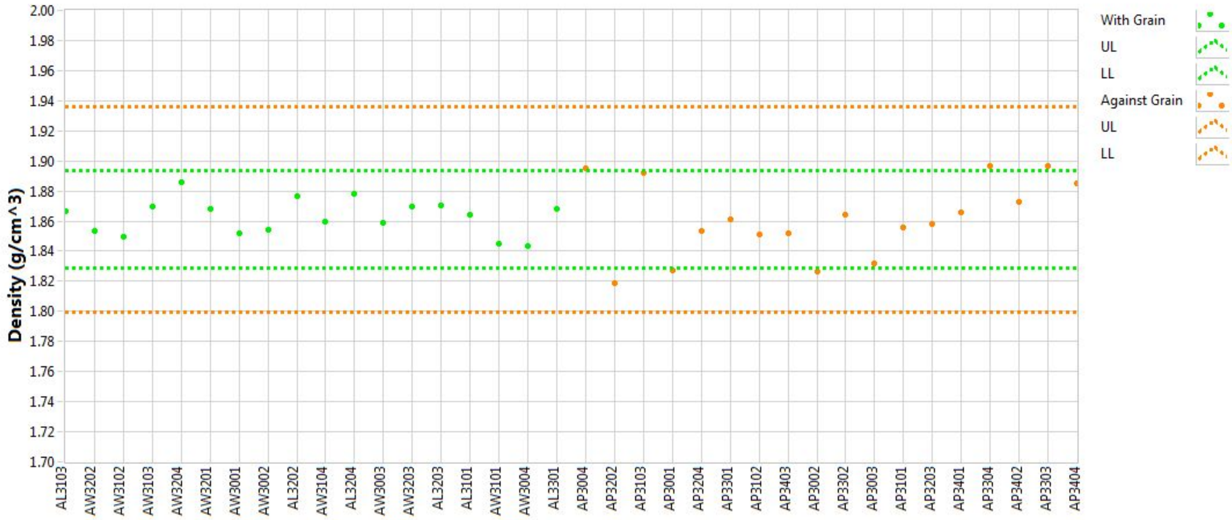

Figure A-43. NBG-17 creep density.

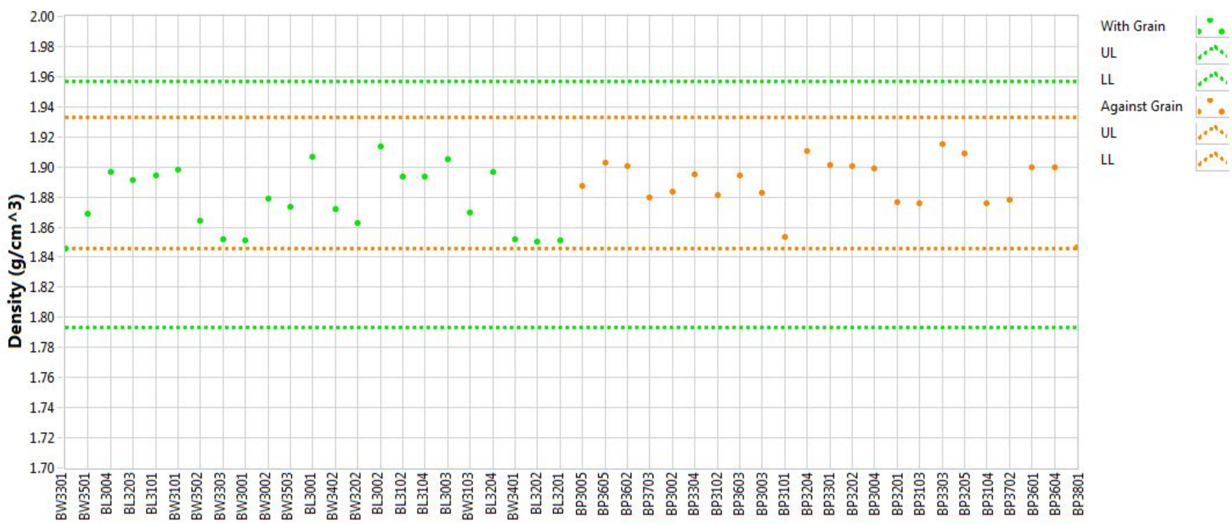

Figure A-44. NBG-18 creep density.

Figure A-45. PCEA creep density.

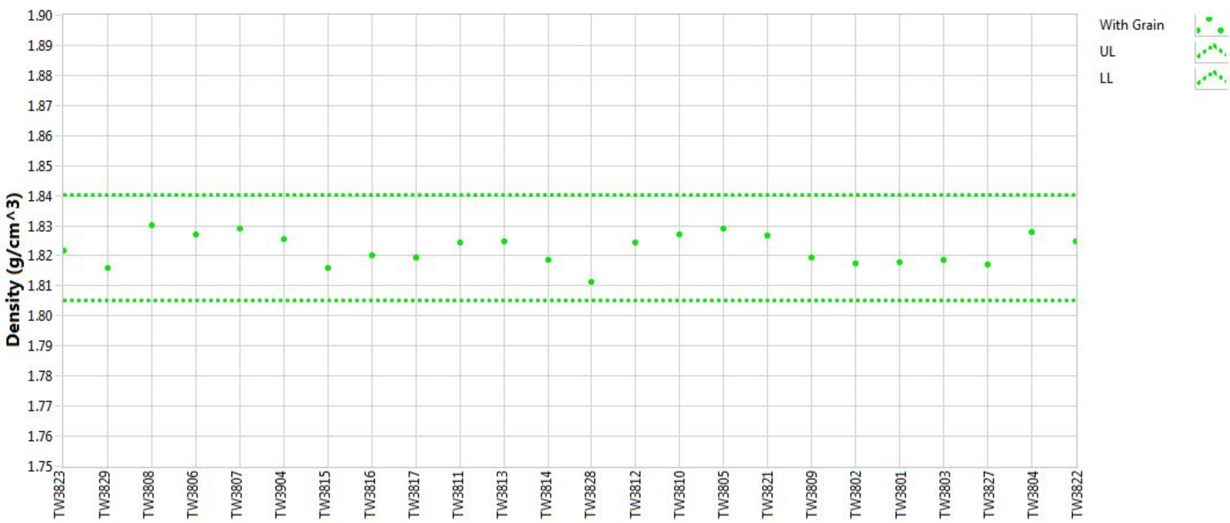

Figure A-46. 2114 piggyback density.

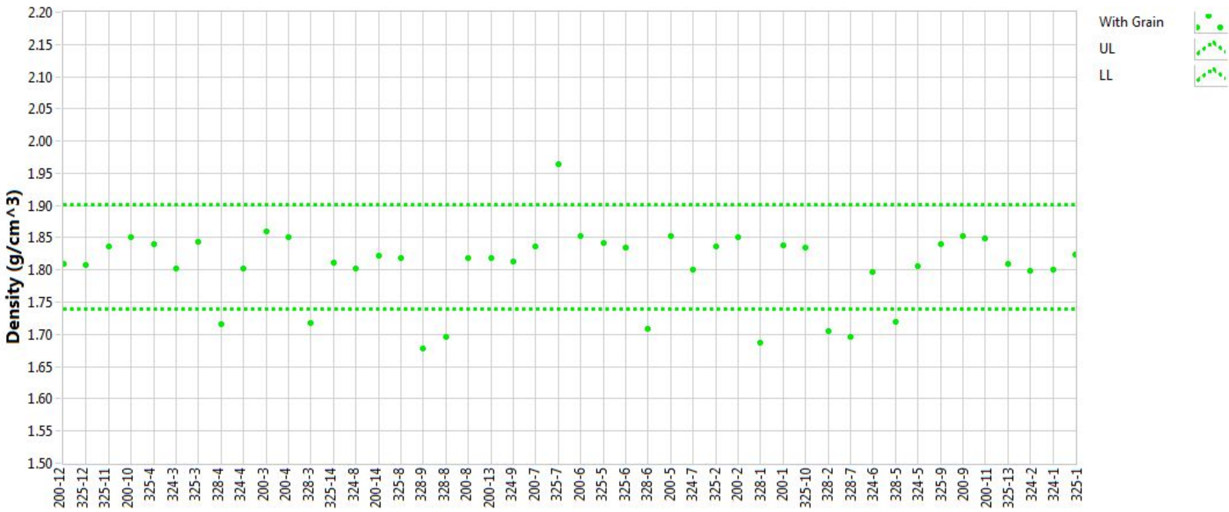

Figure A-47. GrafTech piggyback density.

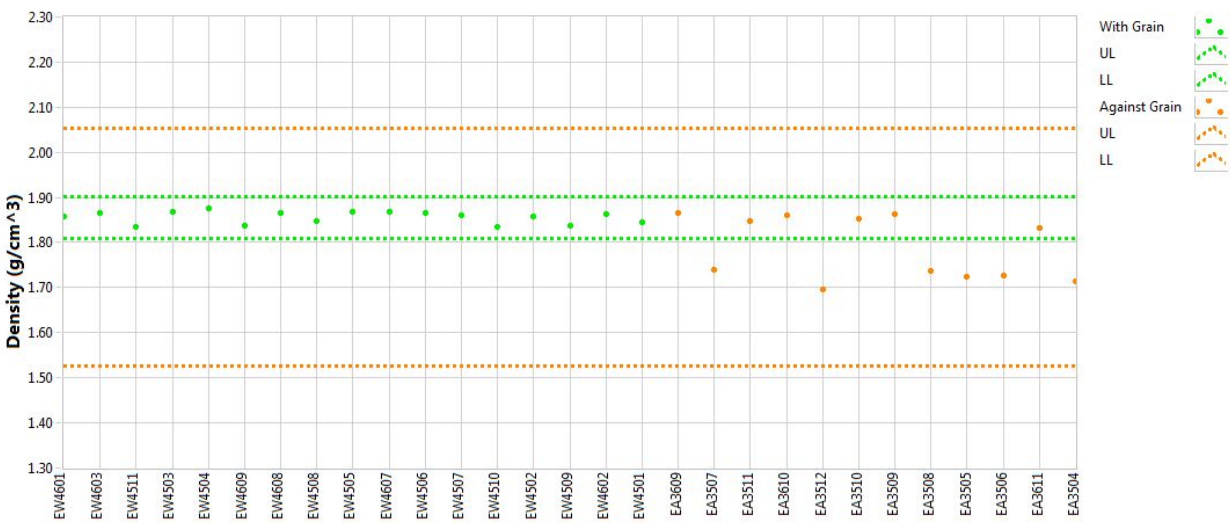

Figure A-48. IG-110 piggyback density.

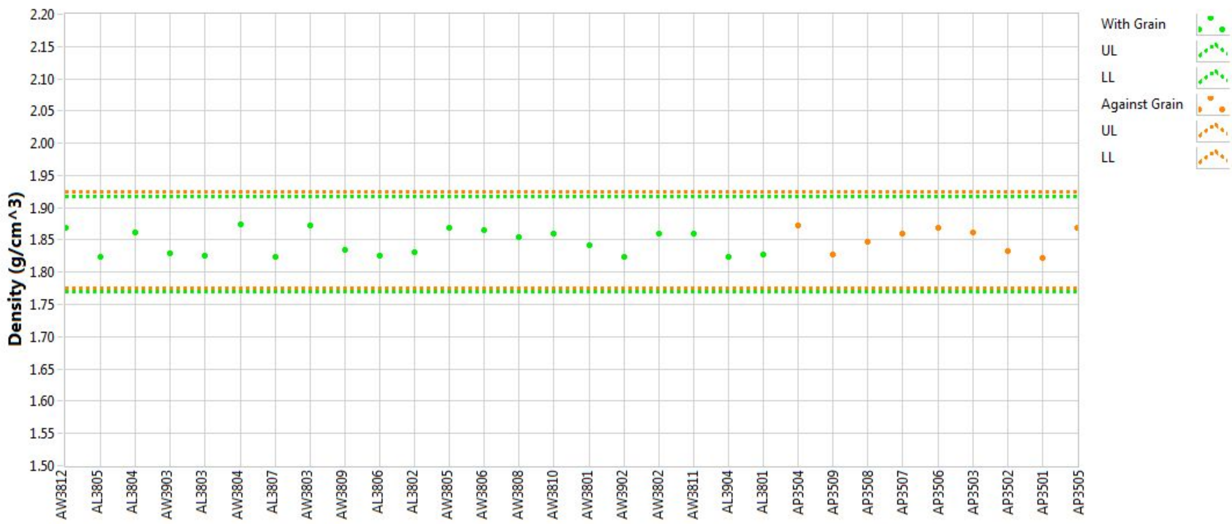

Figure A-49. NBG-17 piggyback density.

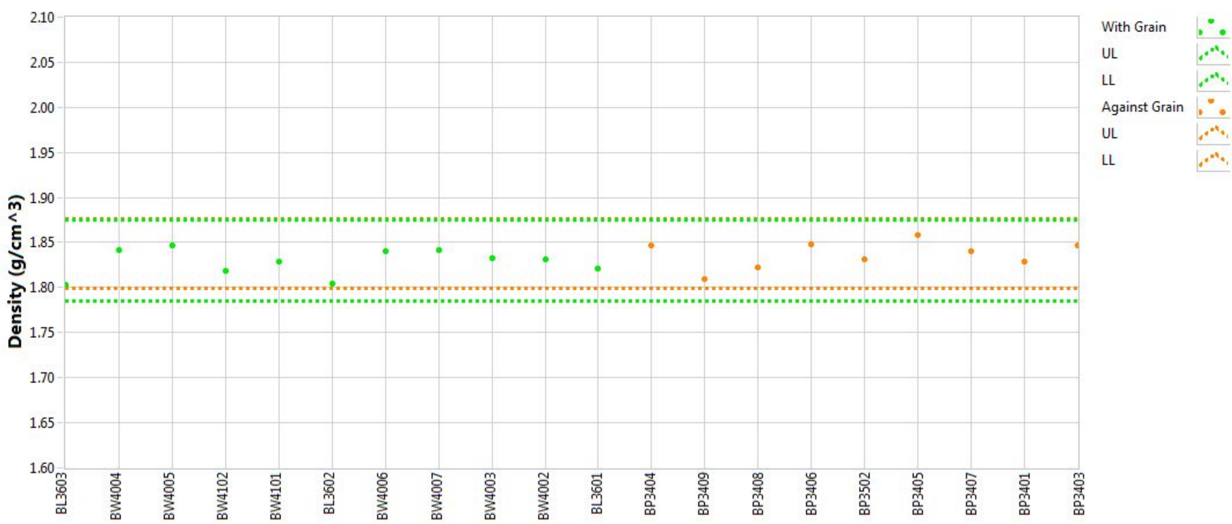

Figure A-50. NBG-18 piggyback density.

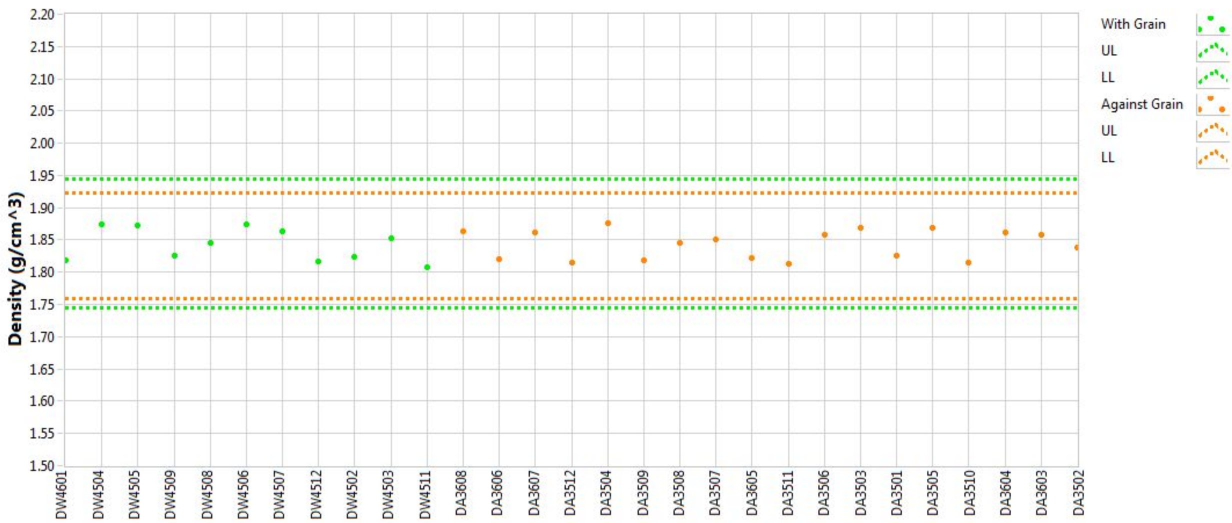

Figure A-51. PCEA piggyback density.

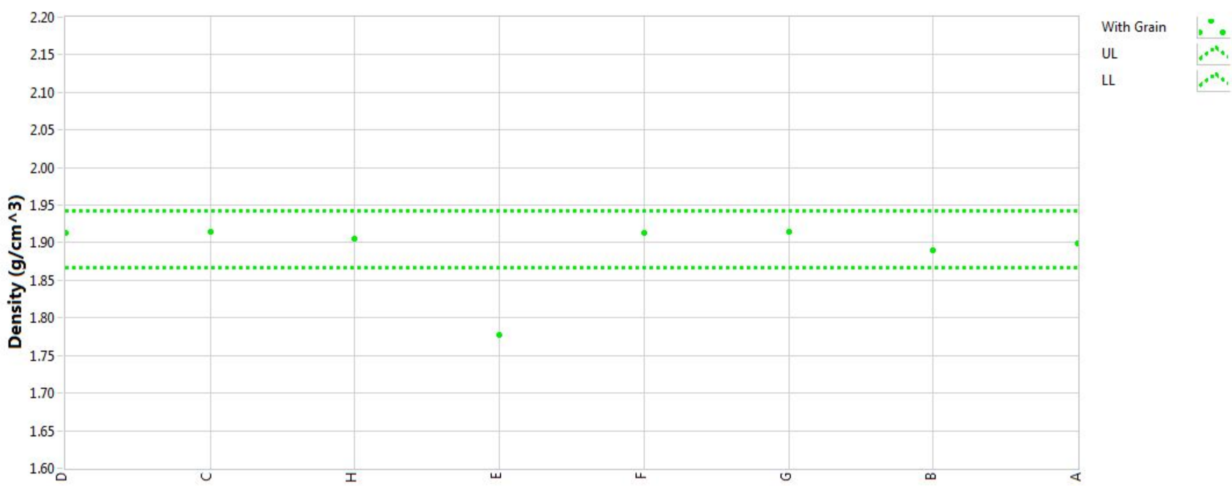

Figure A-52. SGL-SiC piggyback density.

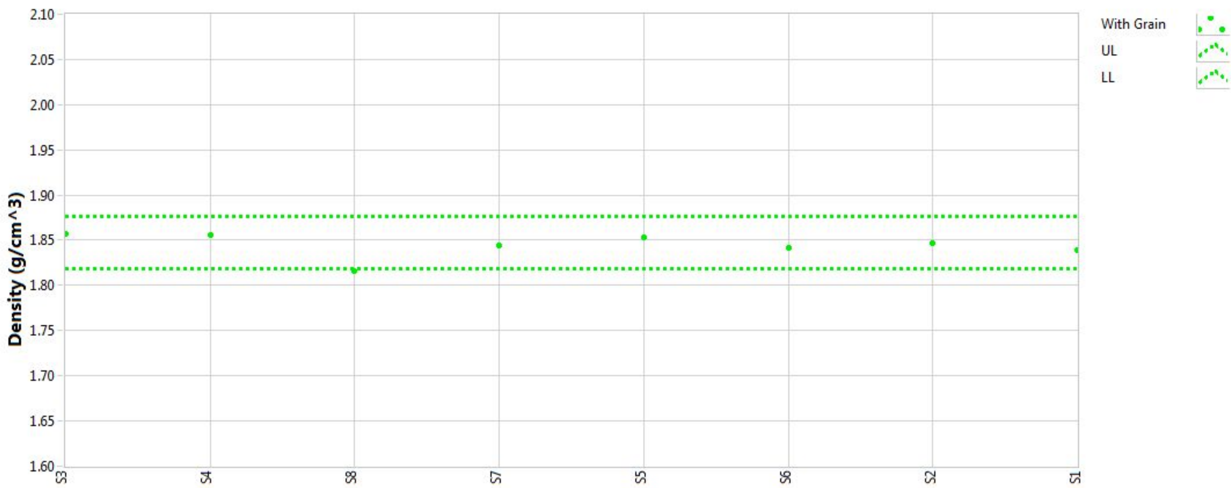

Figure A-53. SGL piggyback density.

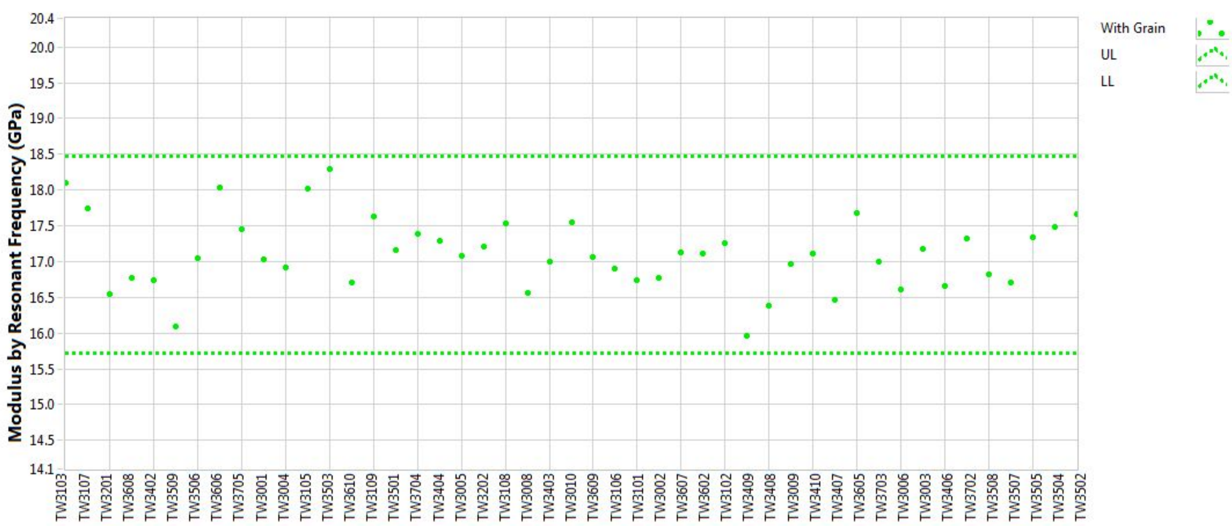

Figure A-54. 2114 creep modulus by resonant frequency.

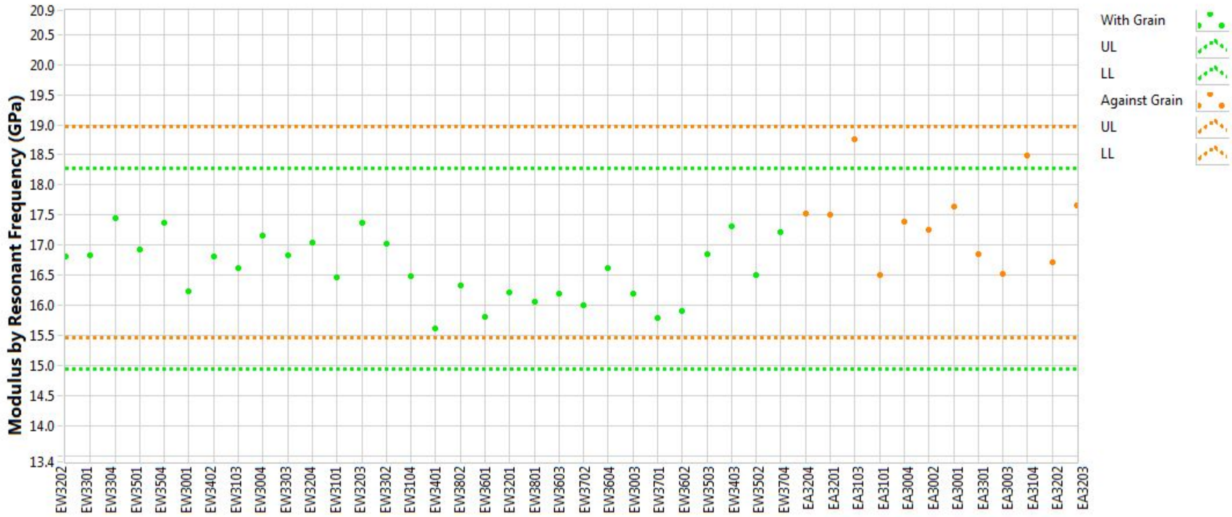

Figure A-55. IG-110 creep modulus by resonant frequency.

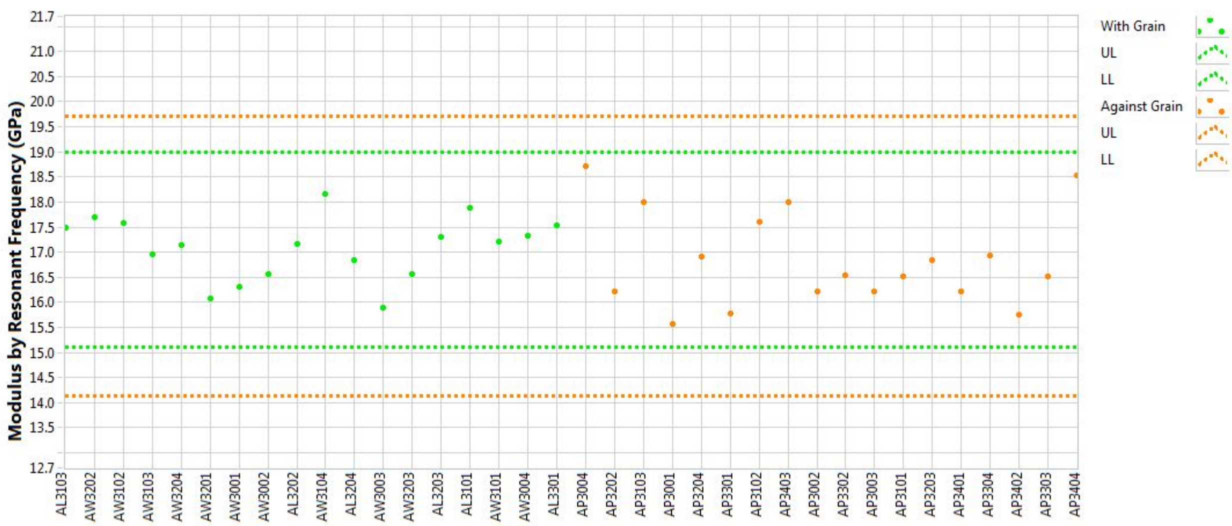

Figure A-56. NBG-17 creep modulus by resonant frequency.

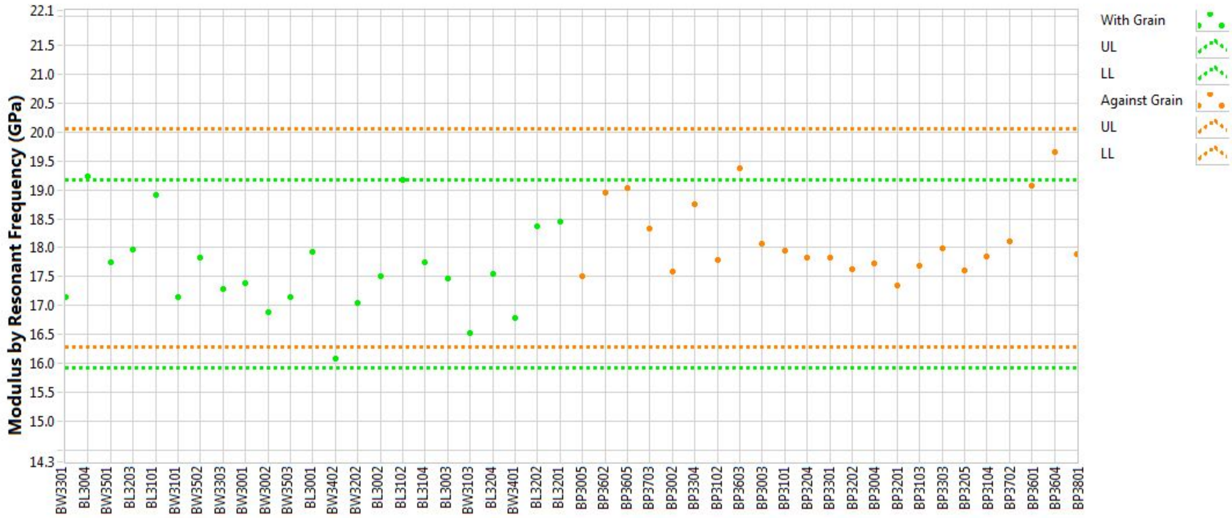

Figure A-57. NBG-18 creep modulus by resonant frequency.

Figure A-58. PCEA creep modulus by resonant frequency.

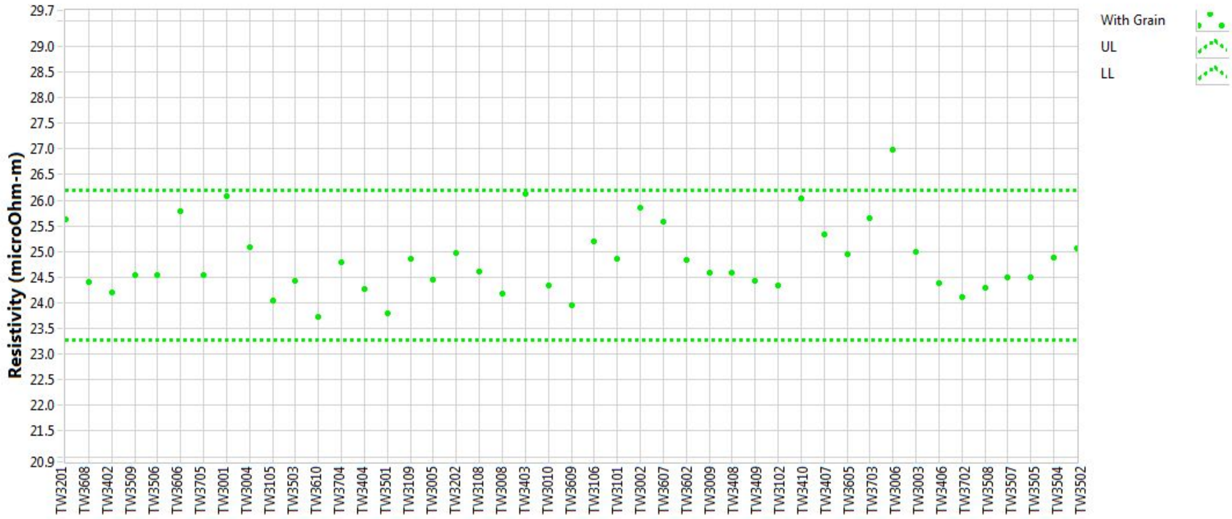

Figure A-59. 2114 creep resistivity.

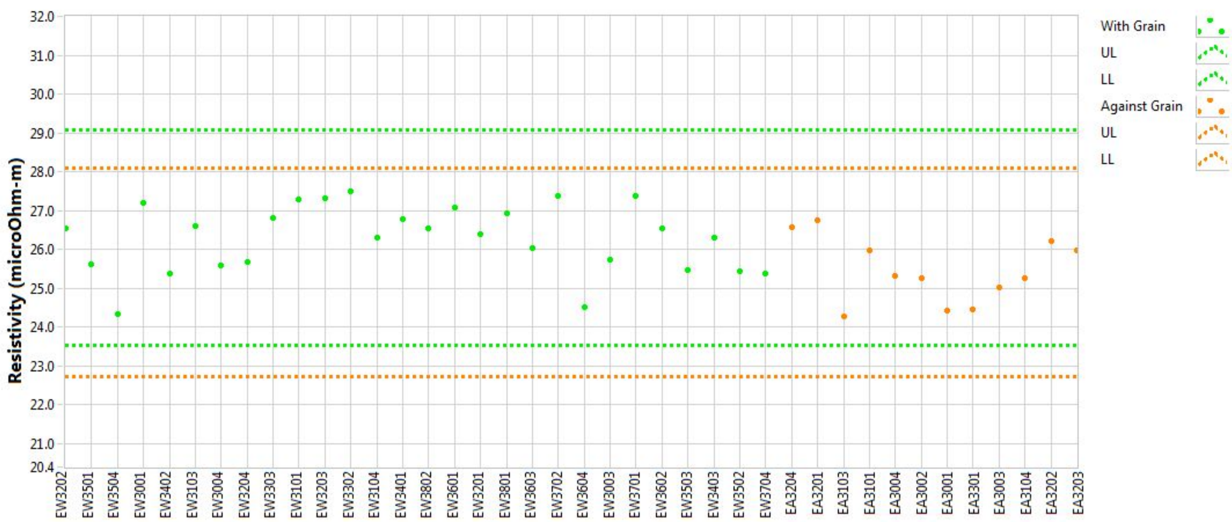

Figure A-60. IG-110 creep resistivity.

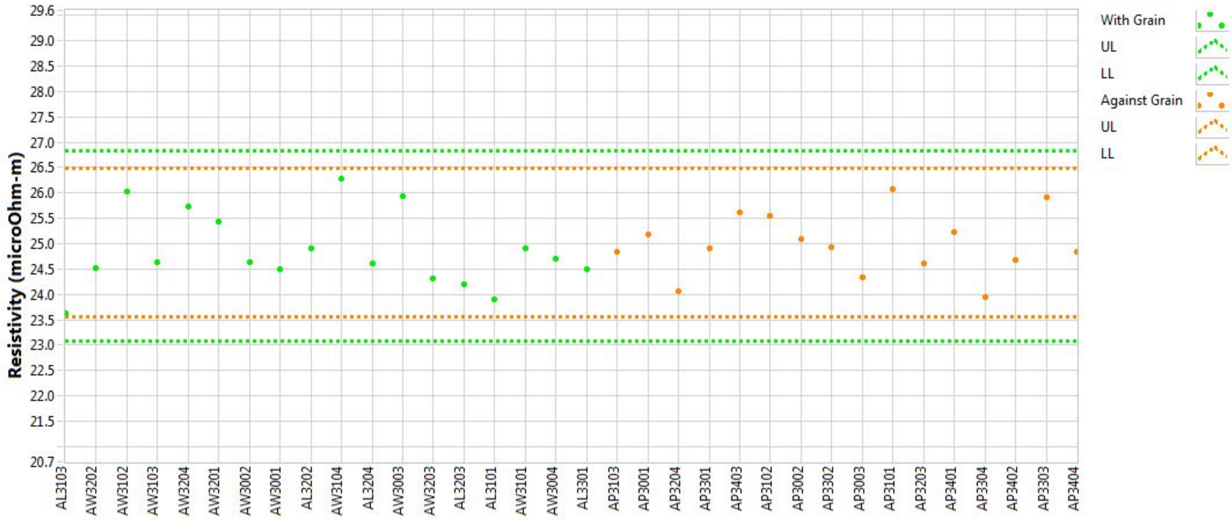

Figure A-61. NBG-17 creep resistivity.

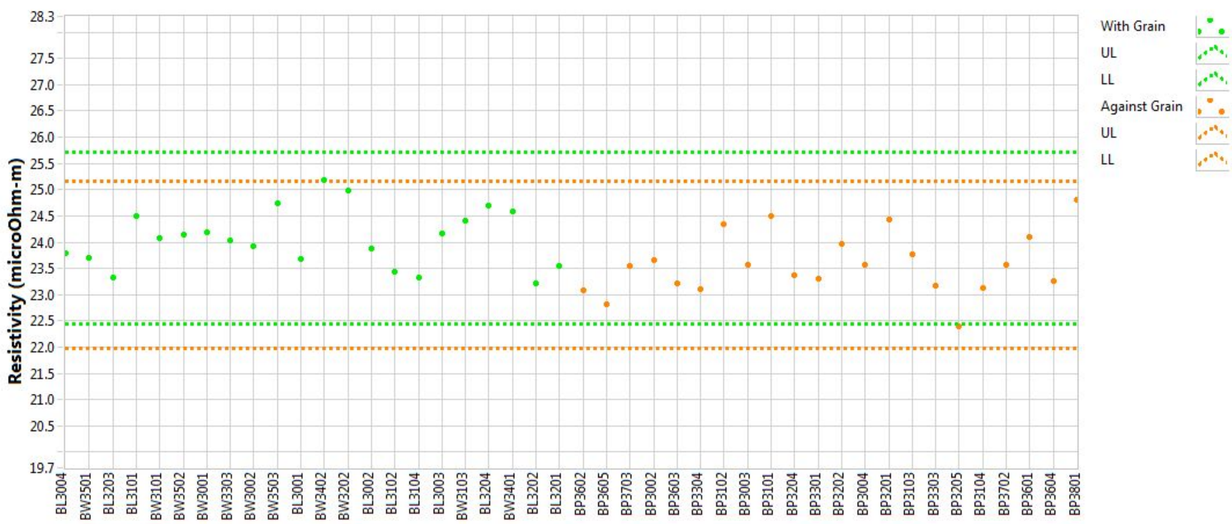

Figure A-62. NBG-18 creep resistivity.

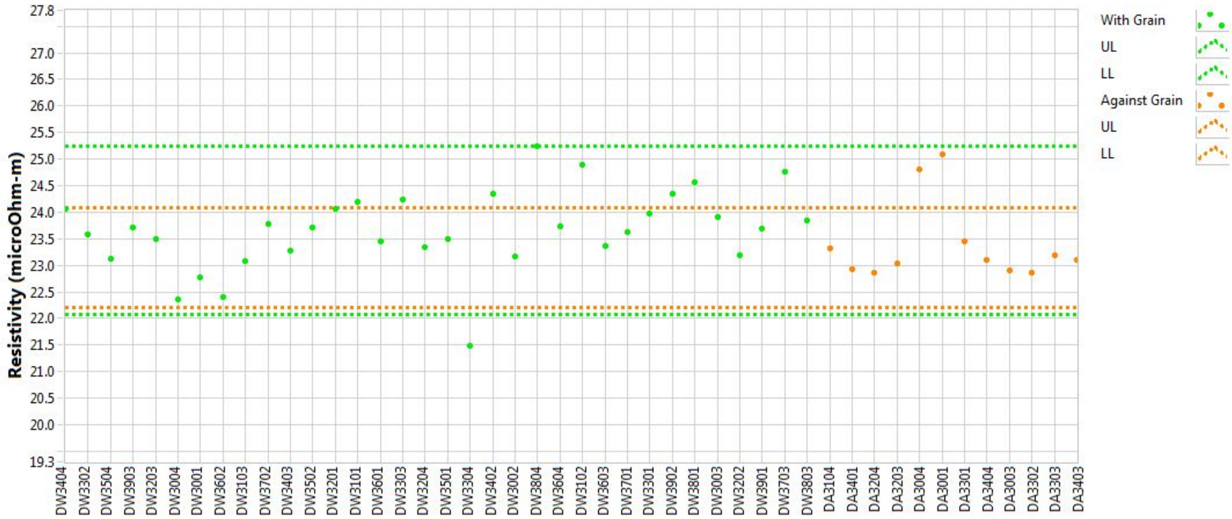

Figure A-63. PCEA creep resistivity.

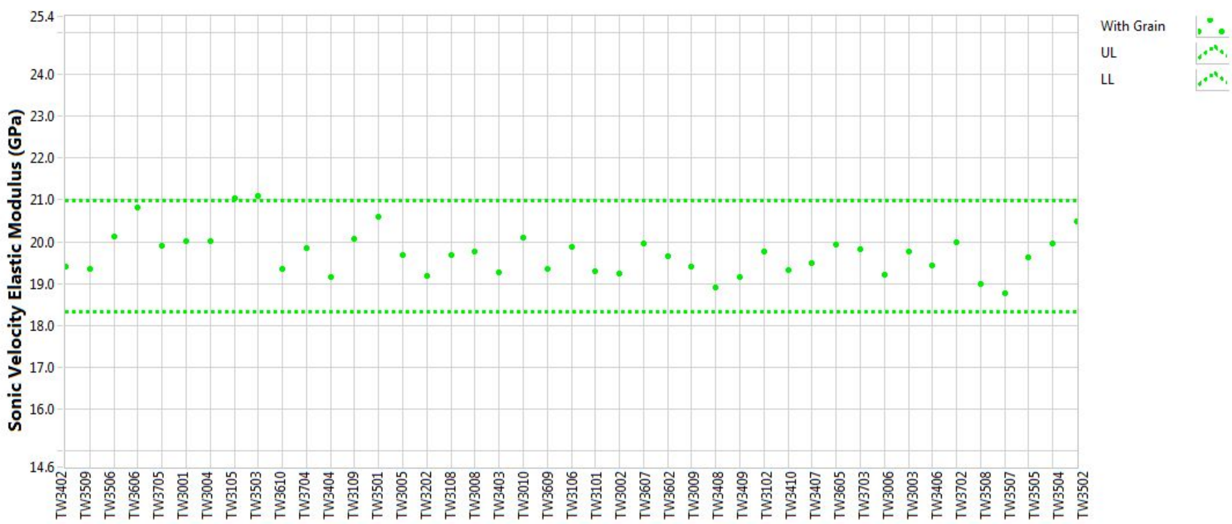

Figure A-64. 2114 creep modulus by sonic velocity.

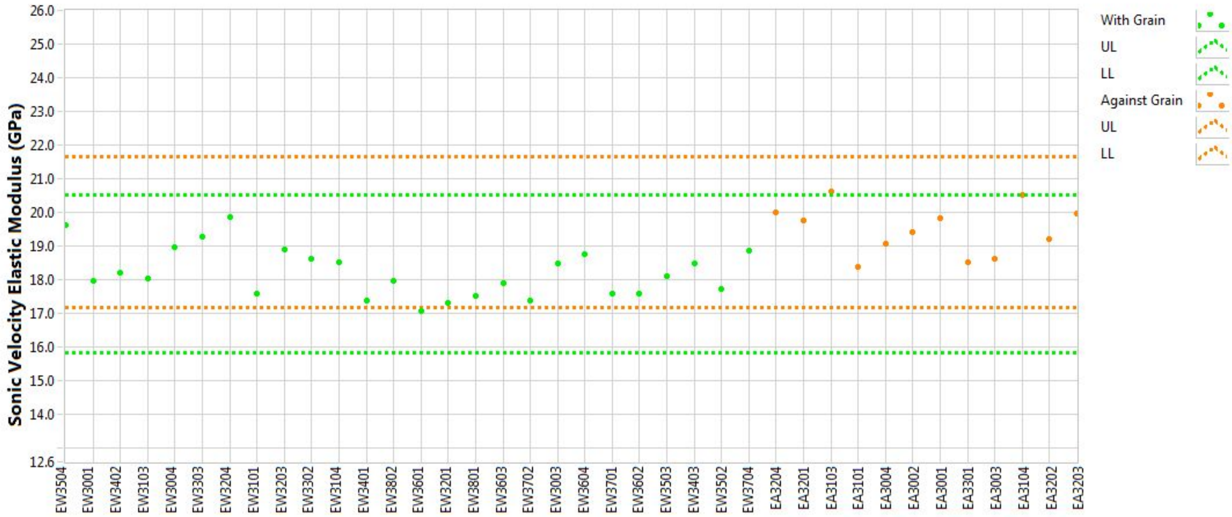

Figure A-65. IG-110 creep modulus by sonic velocity.

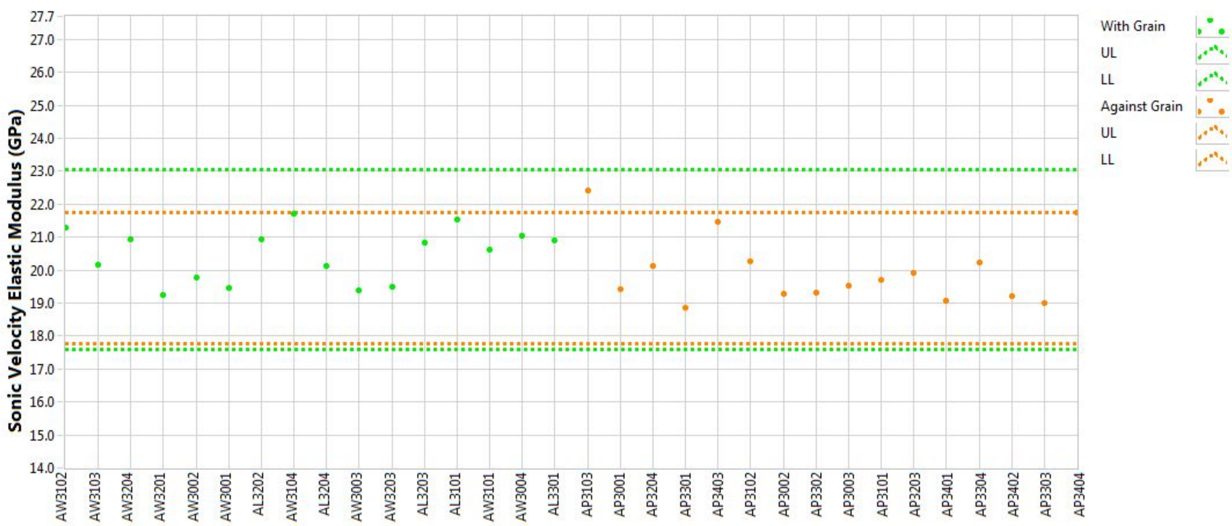

Figure A-66. NBG-17 creep modulus by sonic velocity.

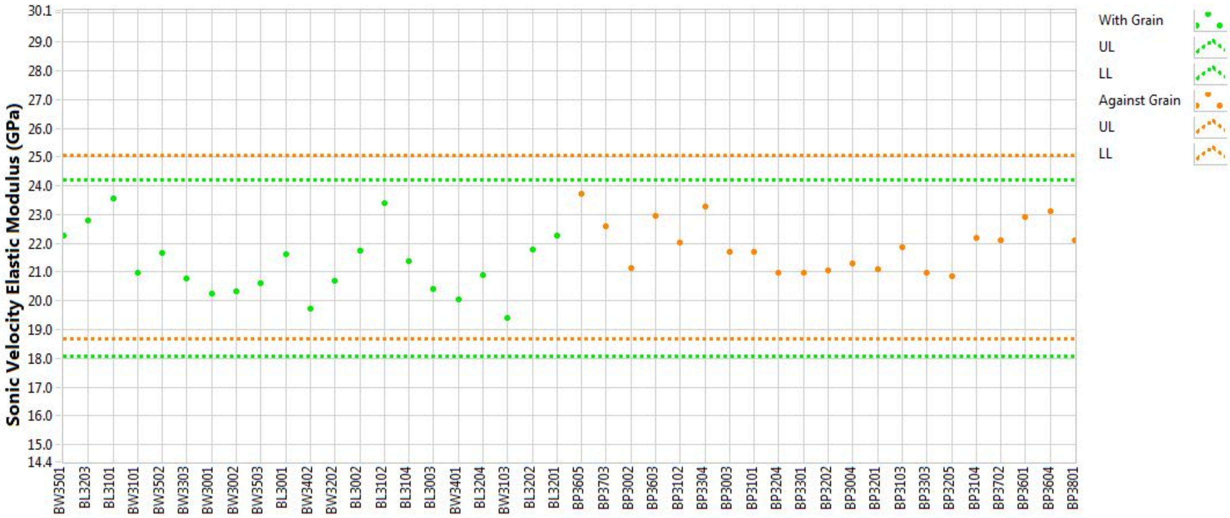

Figure A-67. NBG-18 creep modulus by sonic velocity.

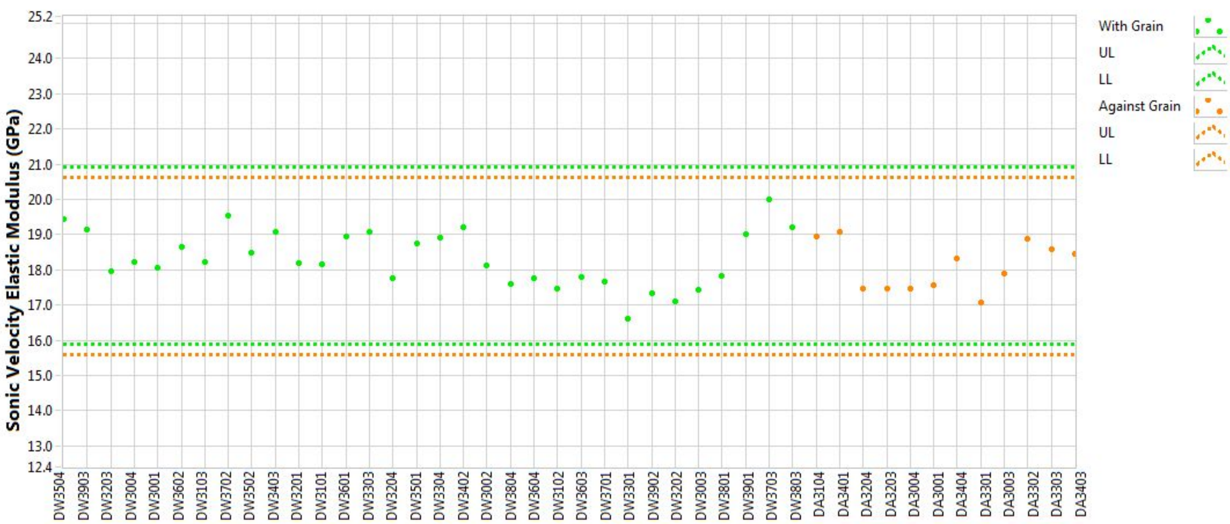

Figure A-68. PCEA creep modulus by sonic velocity.

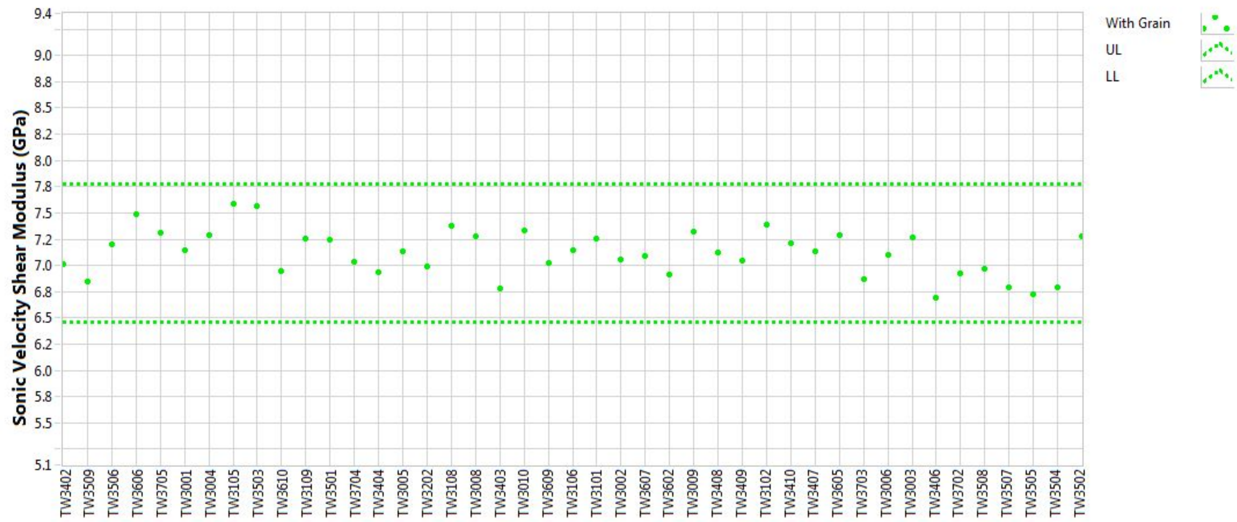

Figure A-69. 2114 creep shear modulus by sonic velocity.

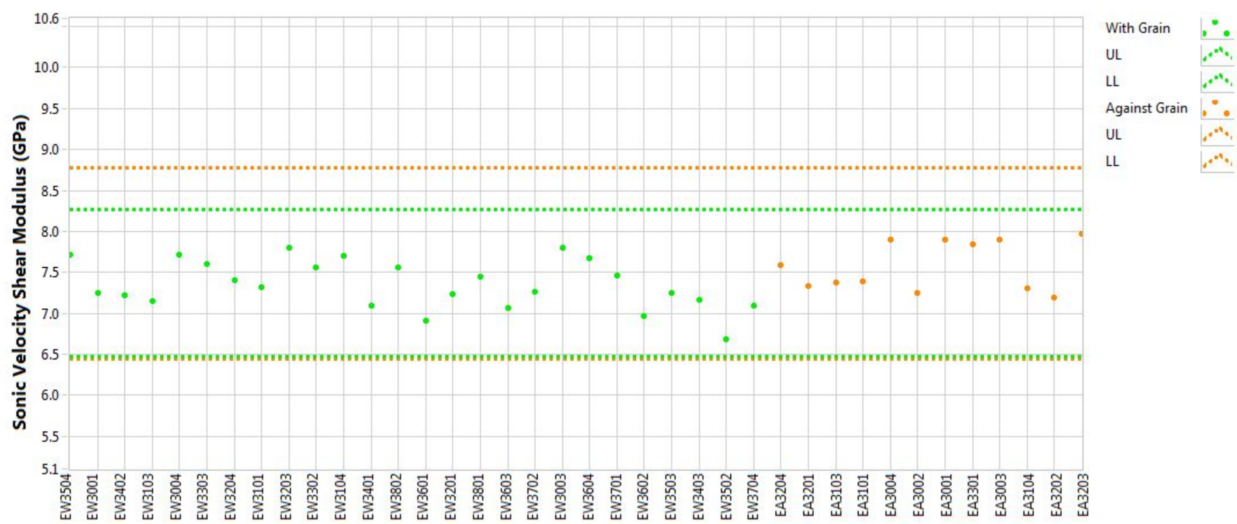

Figure A-70. IG-110 creep shear modulus by sonic velocity.

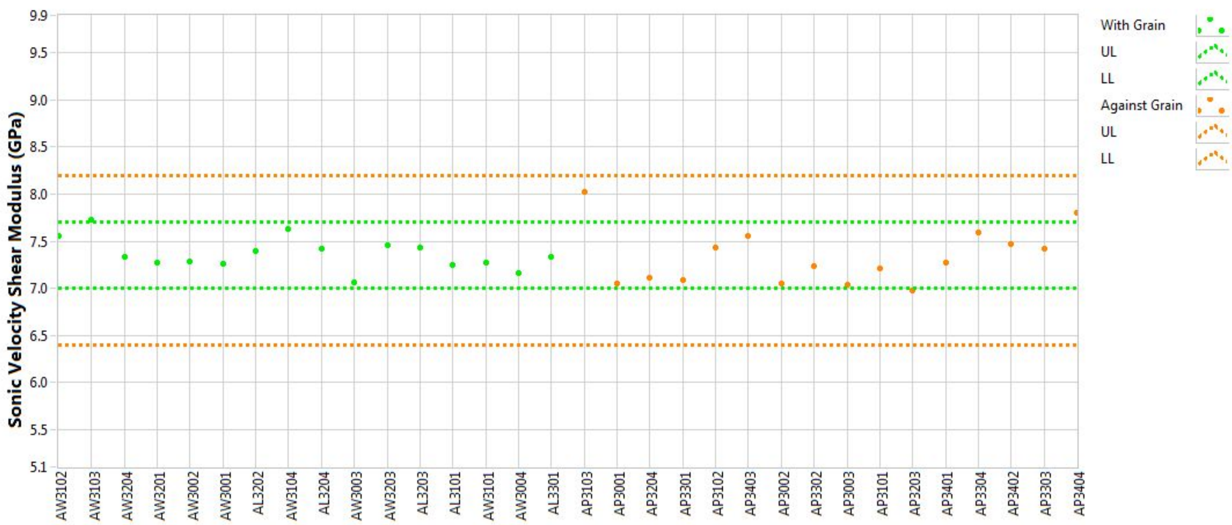

Figure A-71. NBG-17 creep shear modulus by sonic velocity.

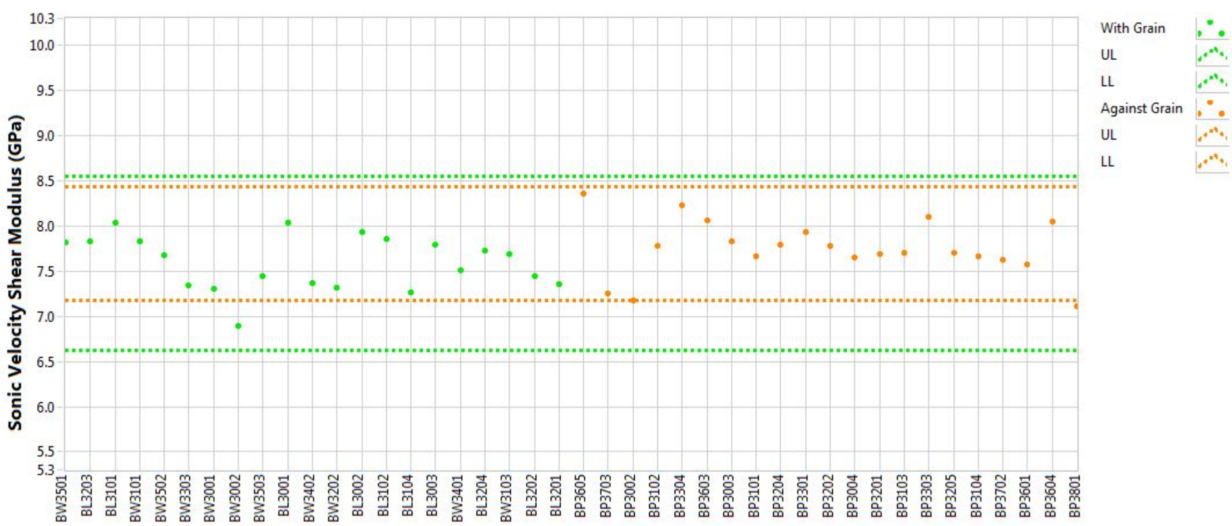

Figure A-72. NBG-18 creep shear modulus by sonic velocity.

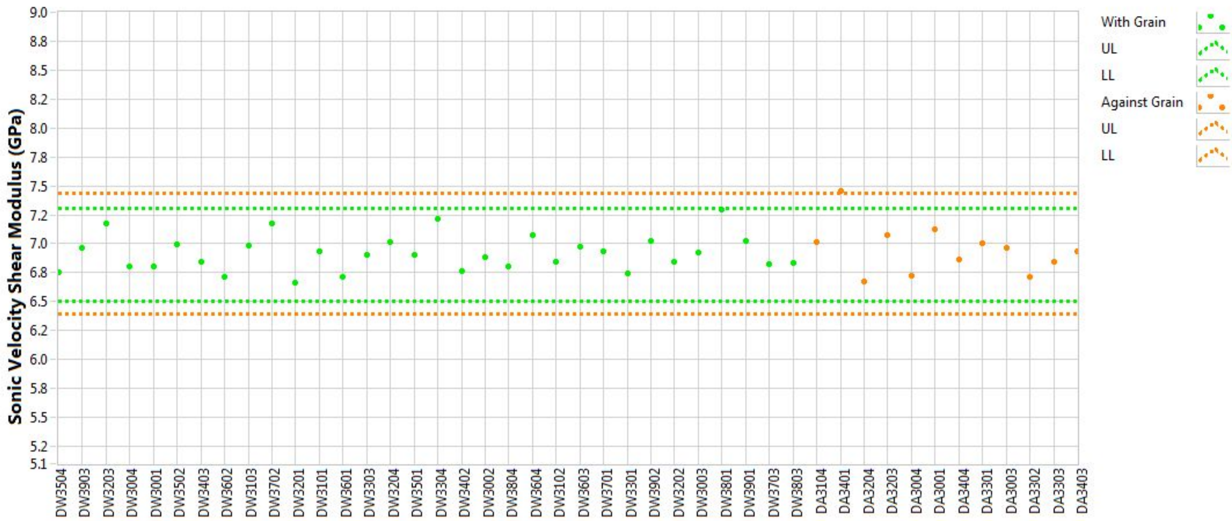

Figure A-73. PCEA creep shear modulus by sonic velocity.

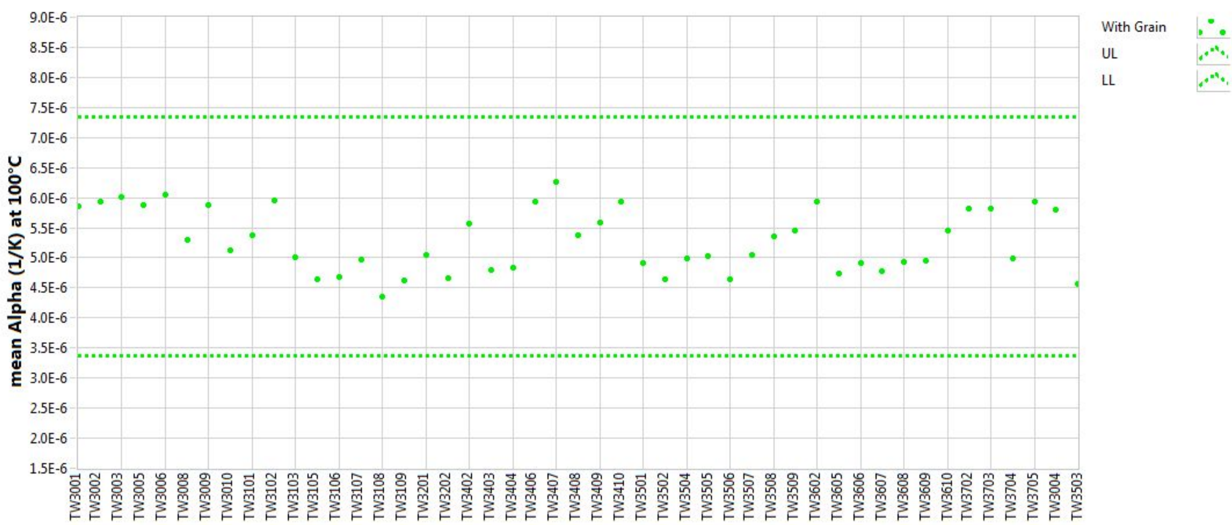

Figure A-74. 2114 creep coefficient of thermal expansion at 100°C.

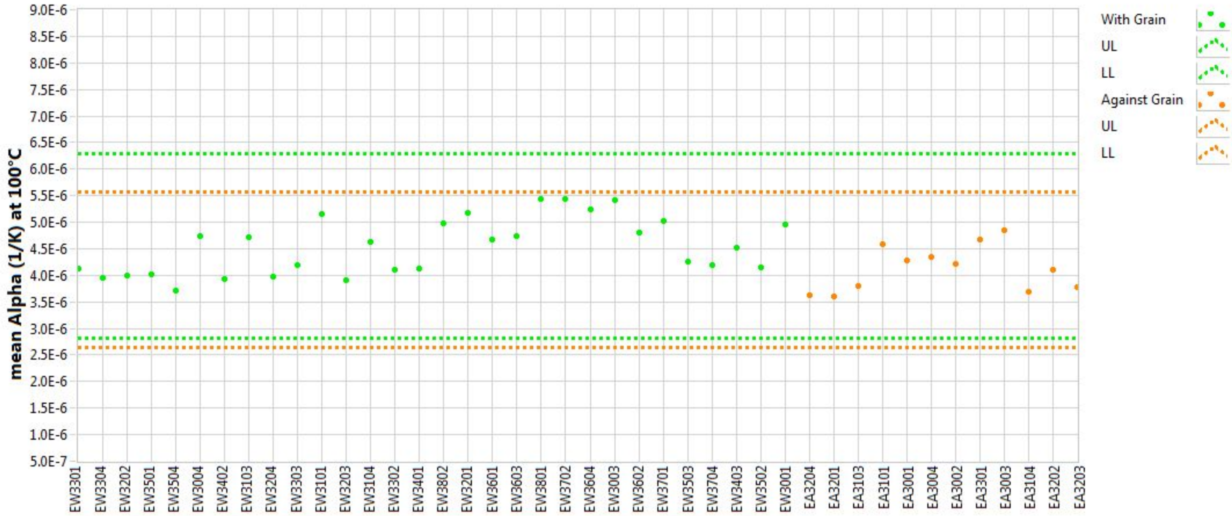

Figure A-75. IG-110 creep coefficient of thermal expansion at 100°C.

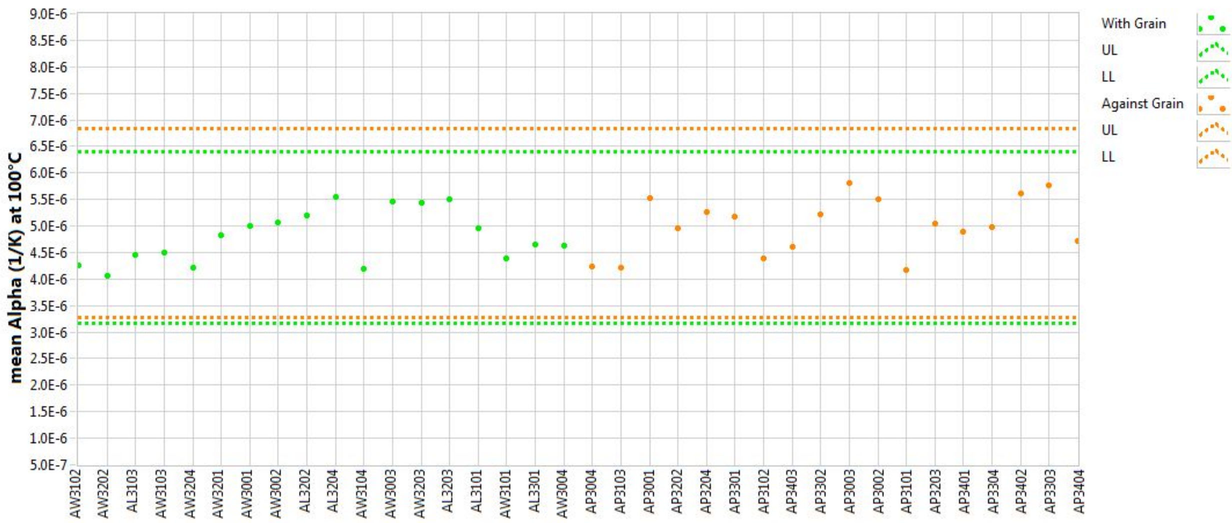

Figure A-76. NBG-17 creep coefficient of thermal expansion at 100°C.

Figure A-77. NBG-18 creep coefficient of thermal expansion at 100°C.

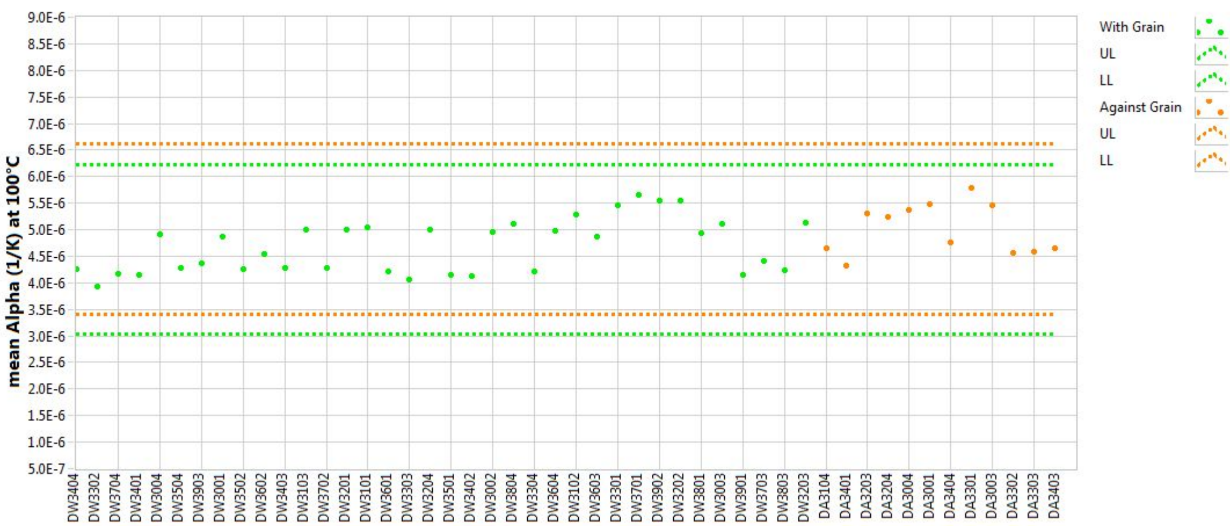

Figure A-78. PCEA creep coefficient of thermal expansion at 100°C.

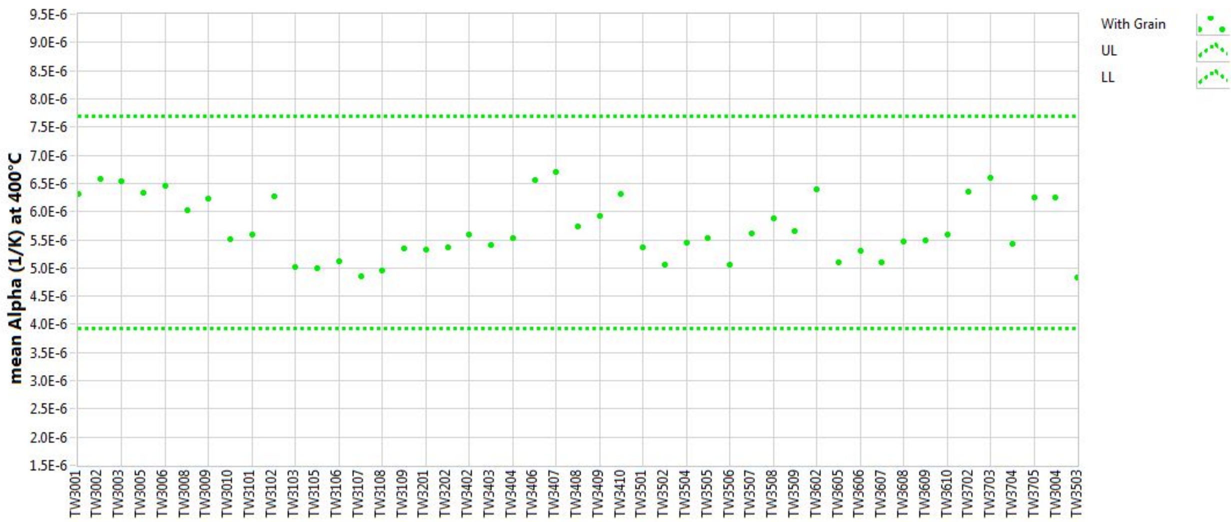

Figure A-79. 2114 creep coefficient of thermal expansion at 400°C.

Figure A-80. IG-110 creep coefficient of thermal expansion at 400°C.

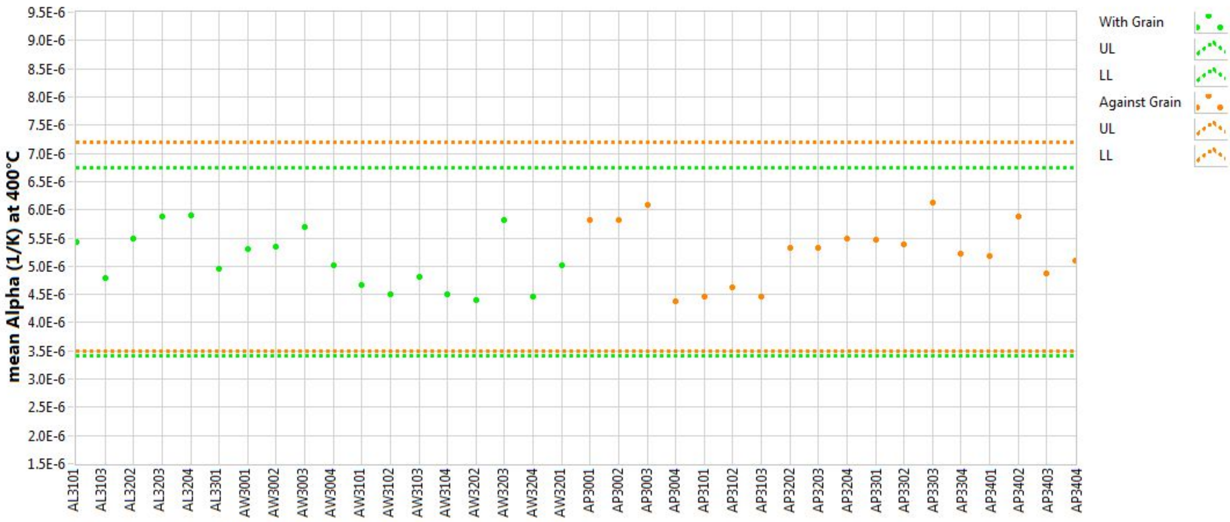

Figure A-81. NBG-17 creep coefficient of thermal expansion at 400°C.

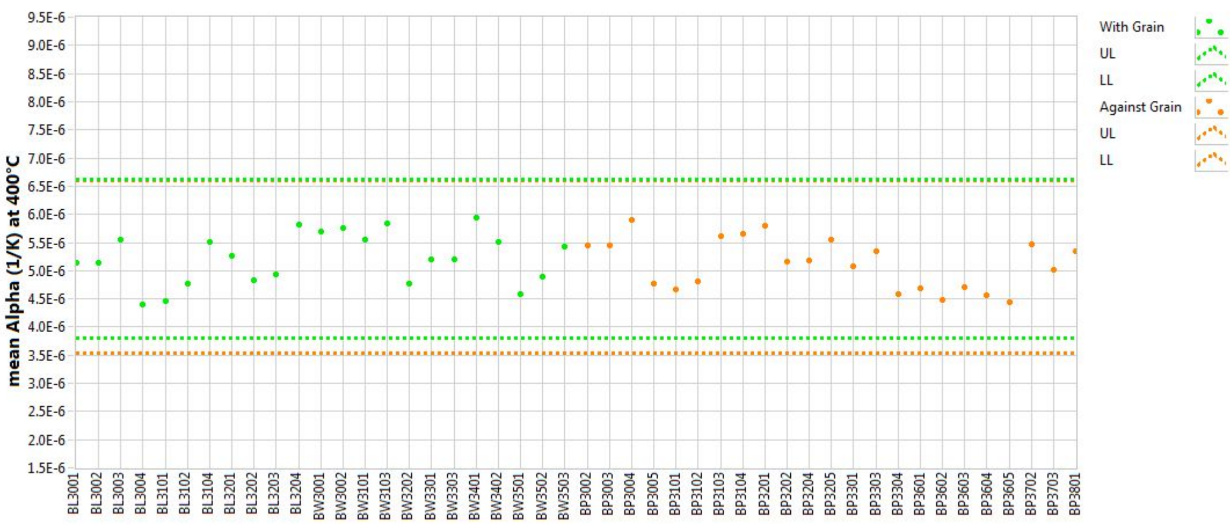

Figure A-82. NBG-18 creep coefficient of thermal expansion at 400°C.

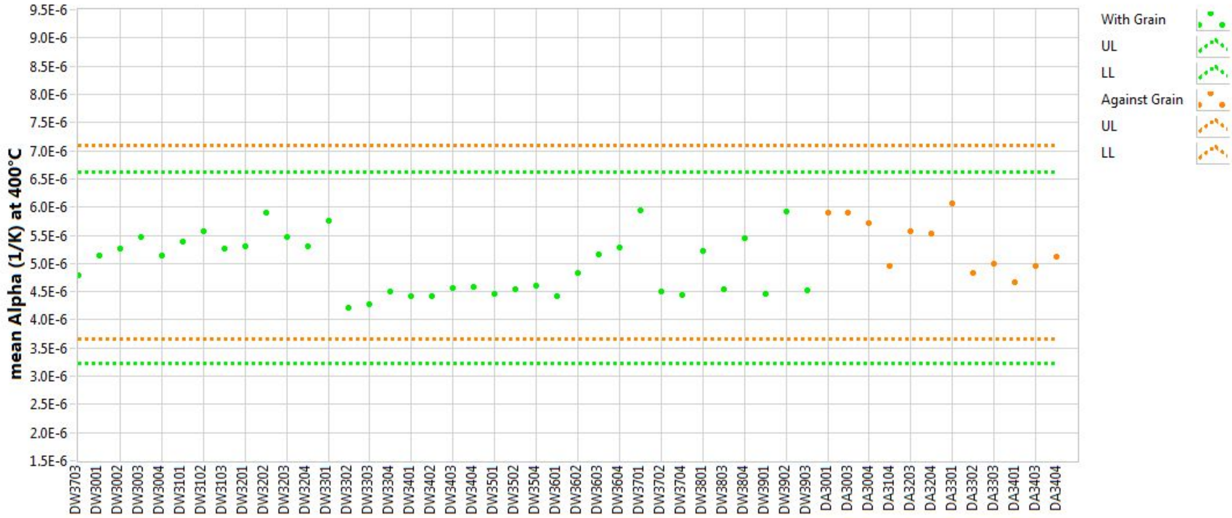

Figure A-83. PCEA creep coefficient of thermal expansion at 400°C.

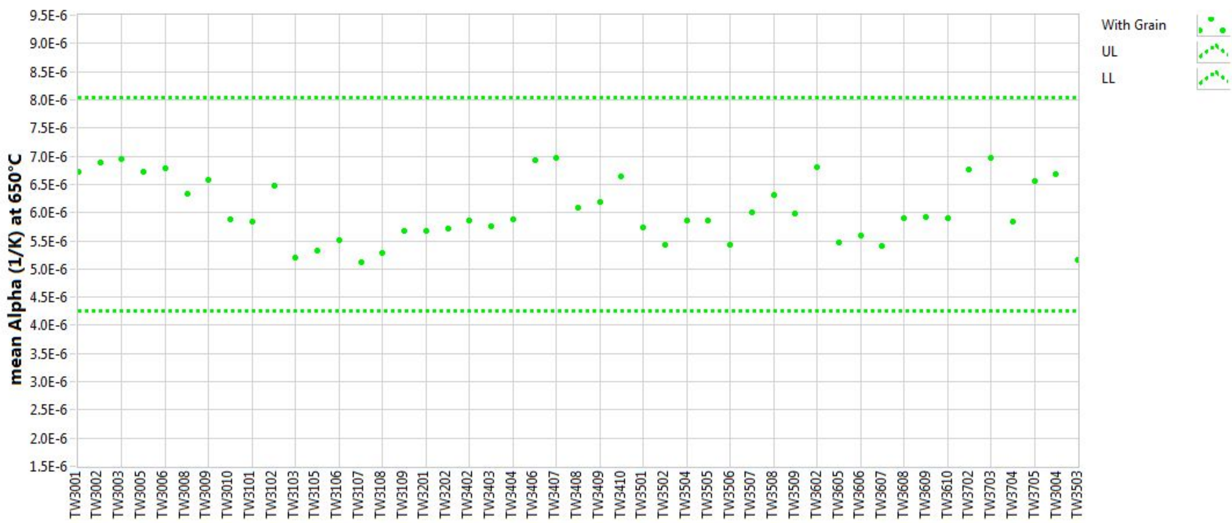

Figure A-84. 2114 creep coefficient of thermal expansion at 650°C.

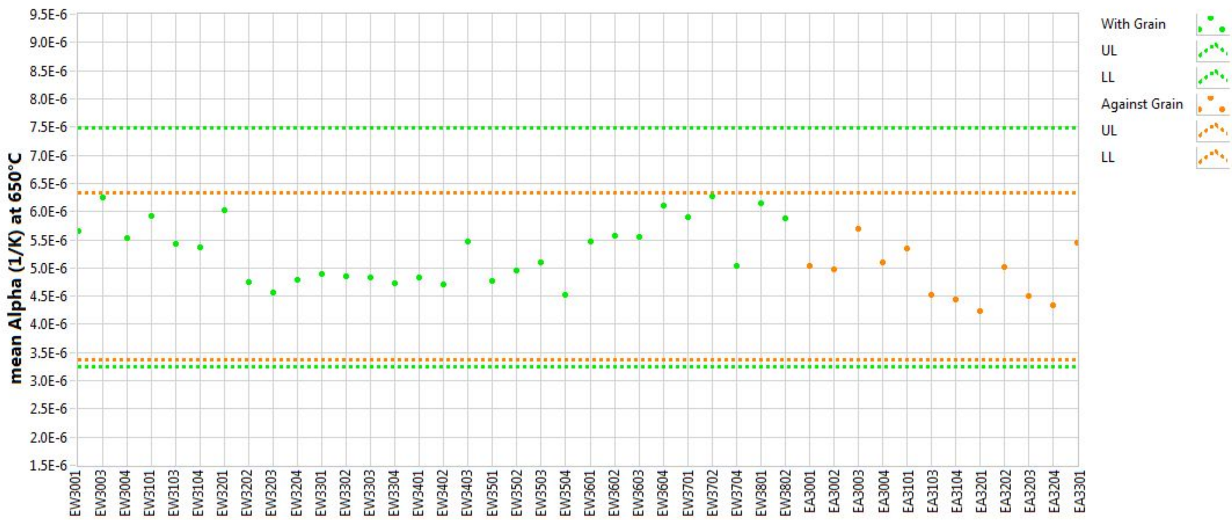

Figure A-85. IG-110 creep coefficient of thermal expansion at 650°C.

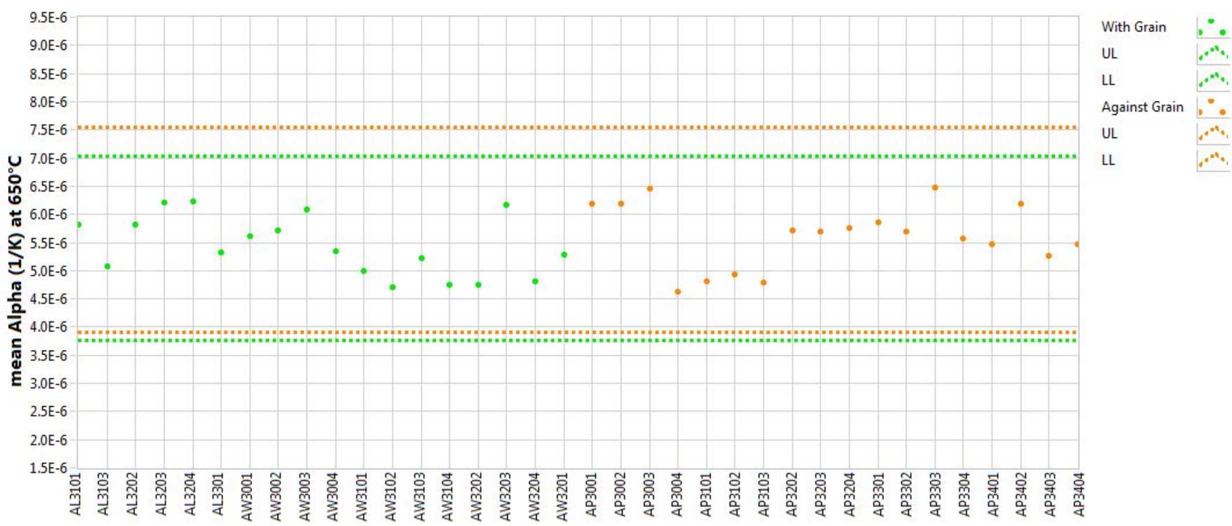

Figure A-86. NBG-17 creep coefficient of thermal expansion at 650°C.

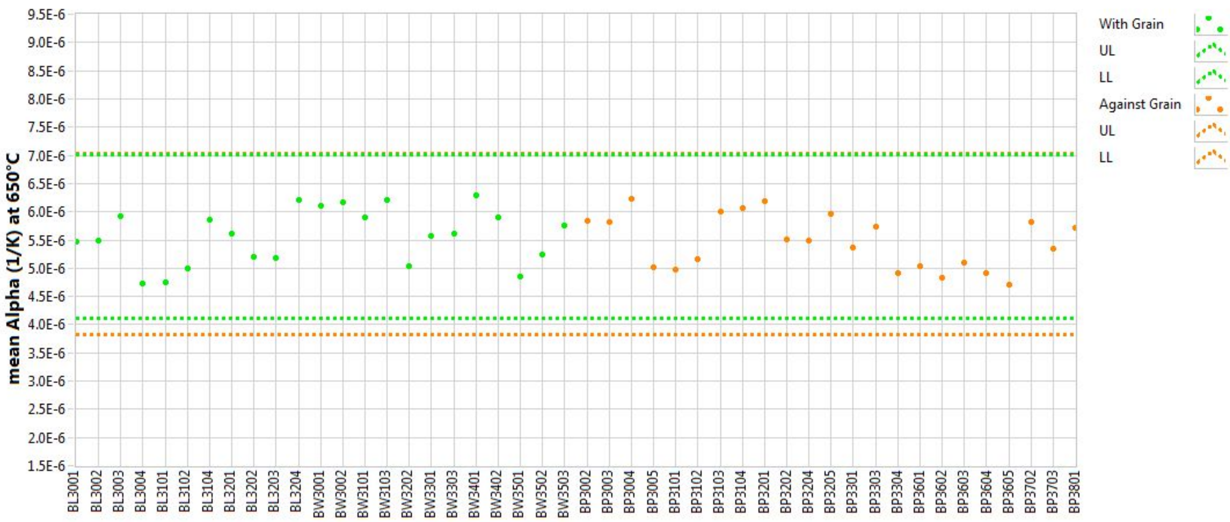

Figure A-87. NBG-18 creep coefficient of thermal expansion at 650°C.

Figure A-88. PCEA creep coefficient of thermal expansion at 650°C.

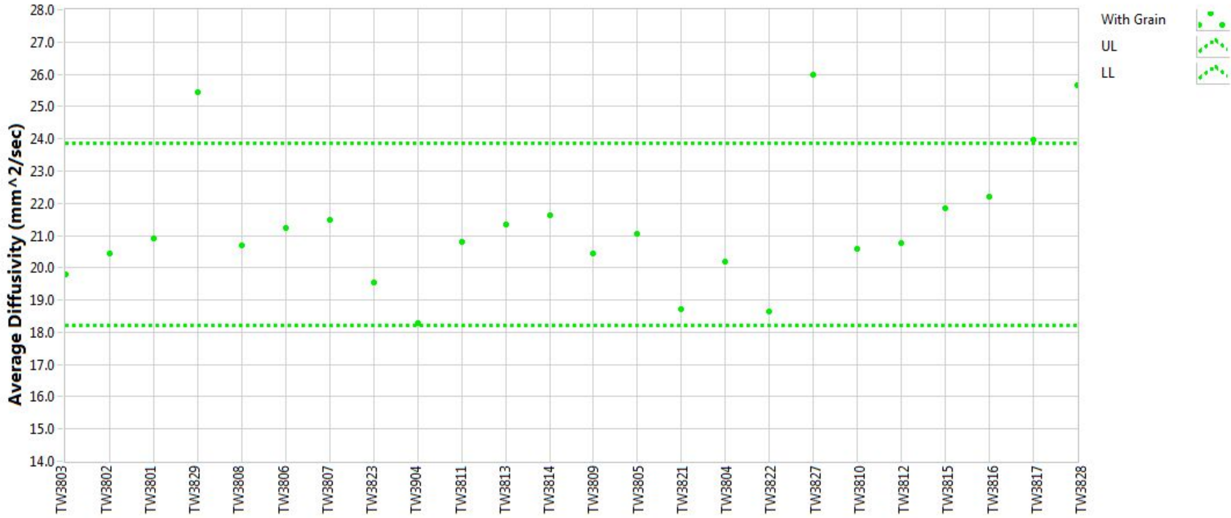

Figure A-89. 2114 piggyback diffusivity at 100°C.

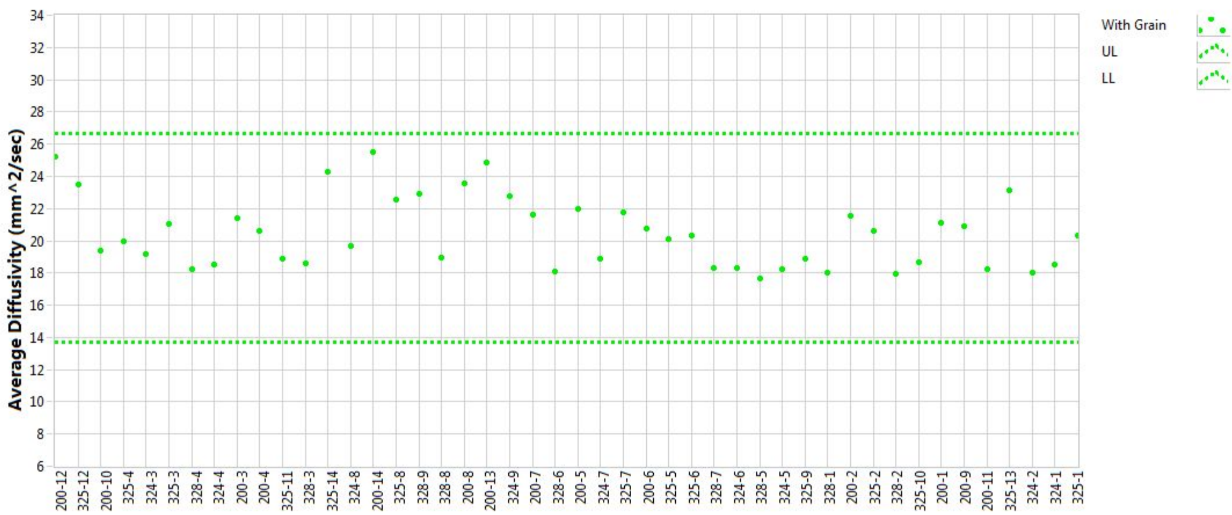

Figure A-90. GrafTech piggyback diffusivity at 100°C.

Figure A-91. IG-110 piggyback diffusivity at 100°C.

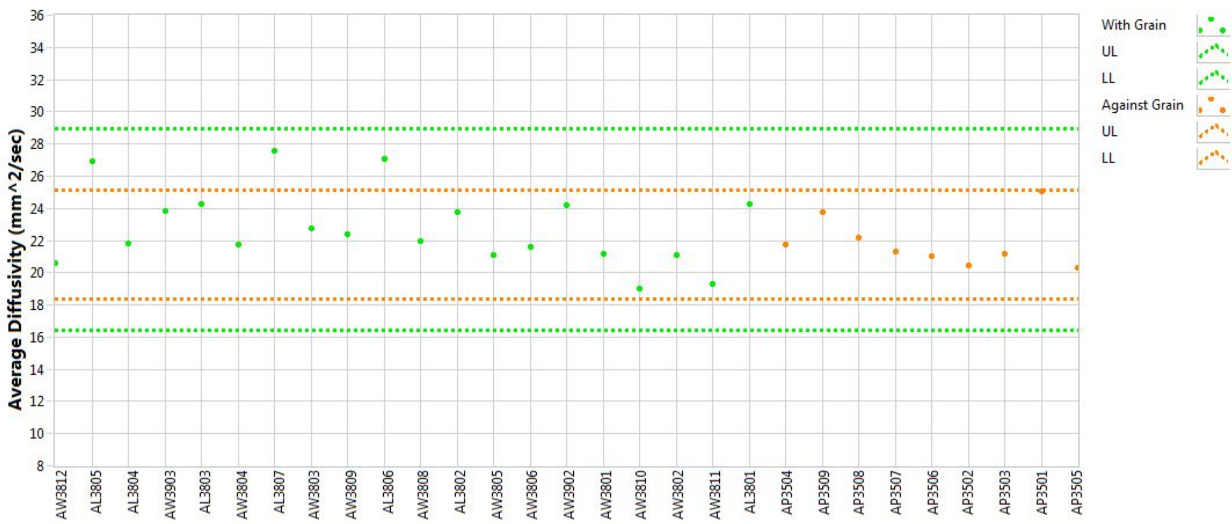

Figure A-92. NBG-17 piggyback diffusivity at 100°C.

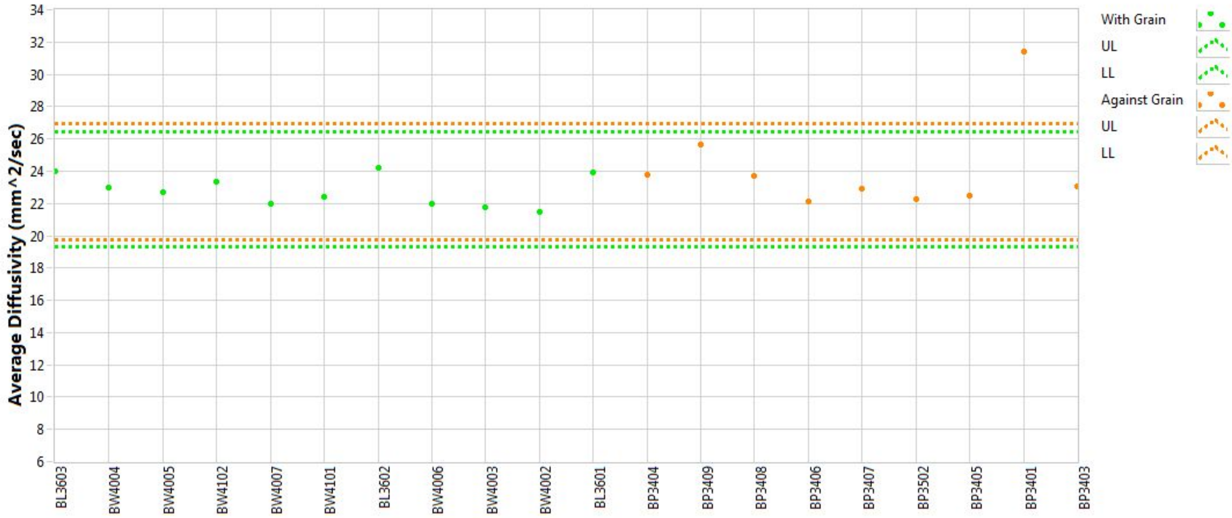

Figure A-93. NBG-18 piggyback diffusivity at 100°C.

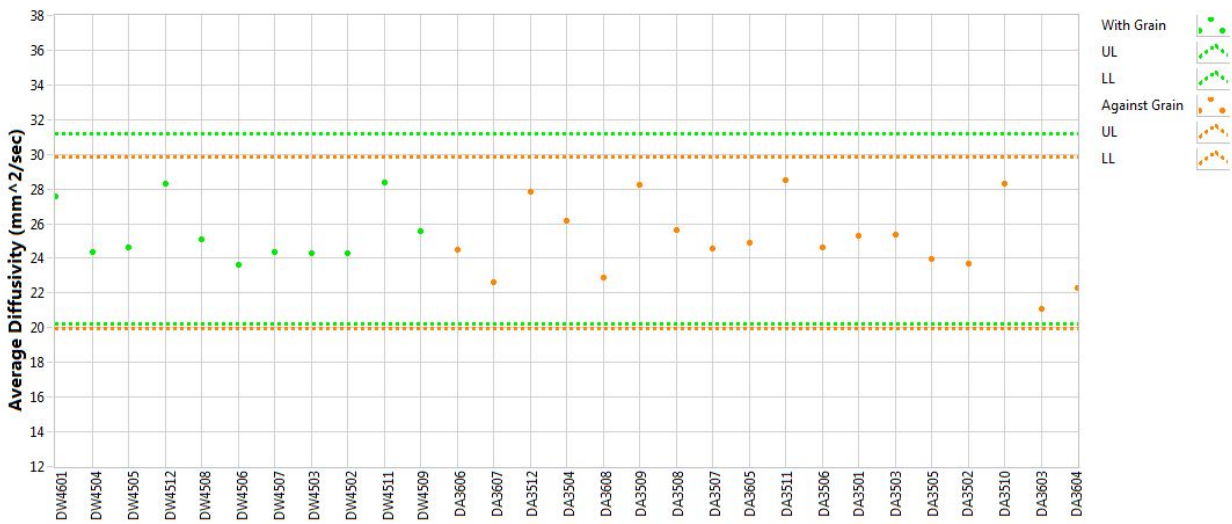

Figure A-94. PCEA piggyback diffusivity at 100°C.

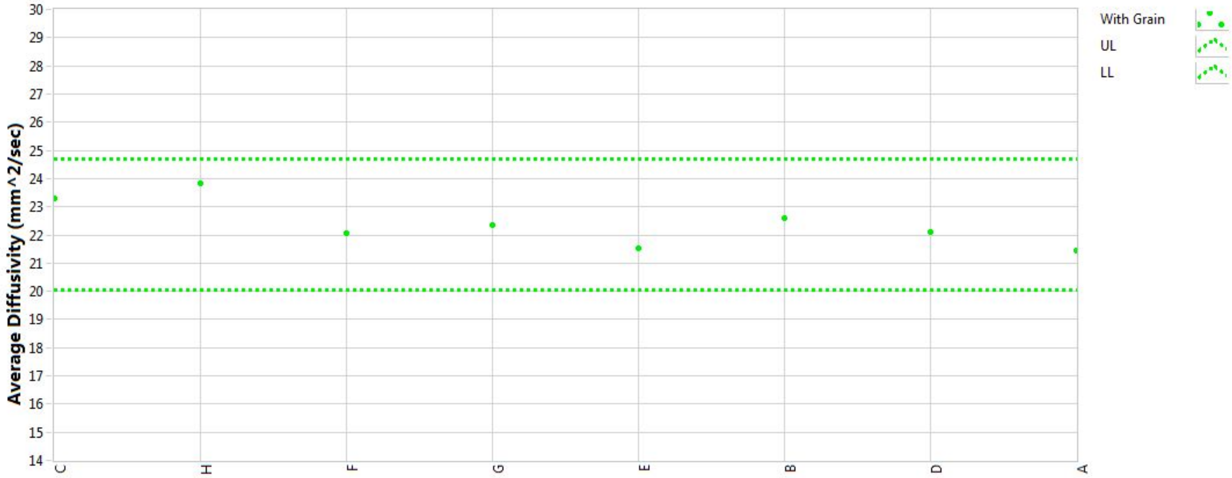

Figure A-95. SGL-SiC piggyback diffusivity at 100°C.

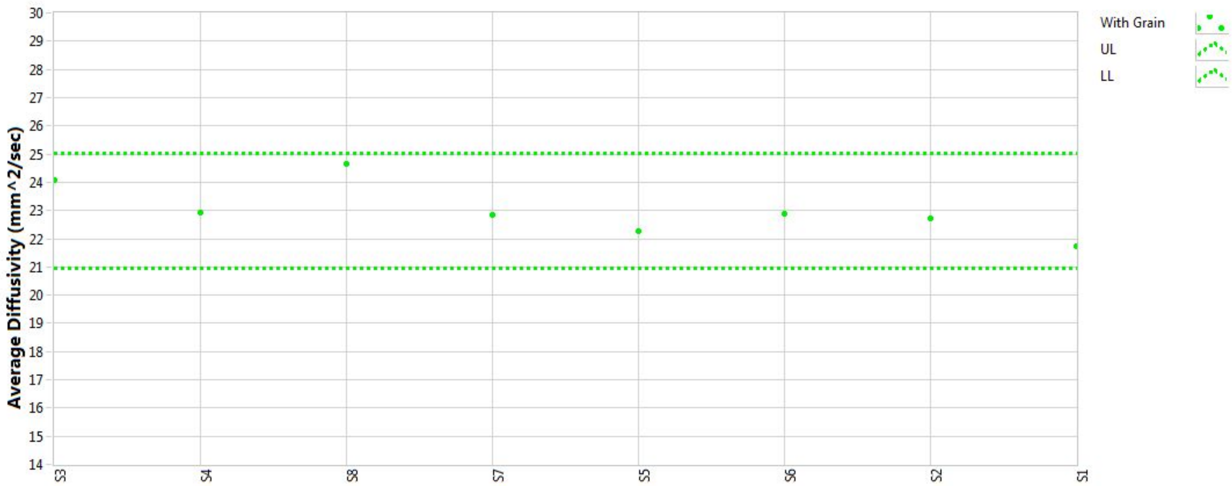

Figure A-96. SGL piggyback diffusivity at 100°C.

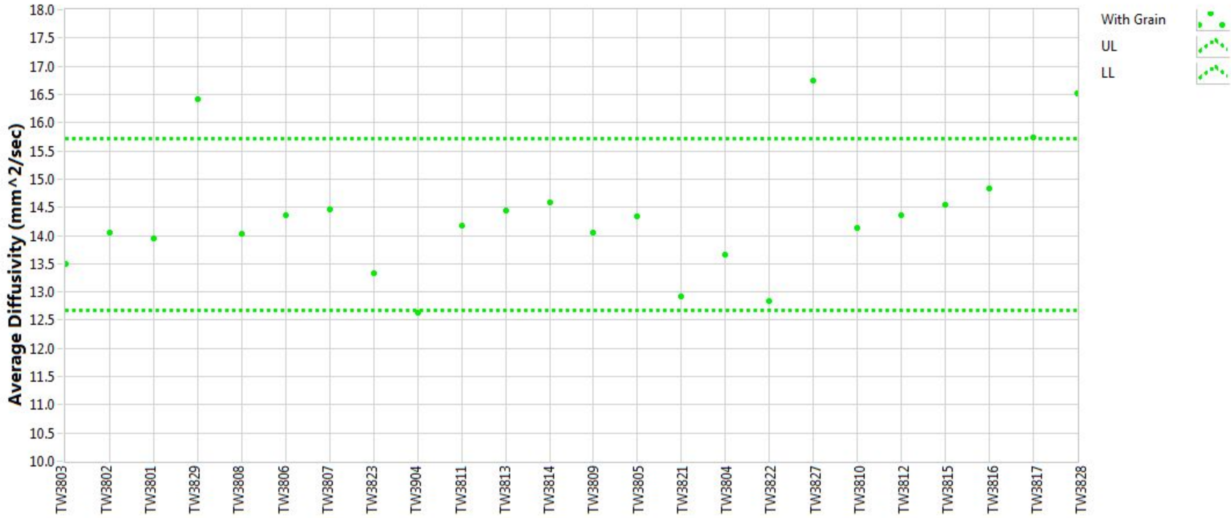

Figure A-97. 2114 piggyback diffusivity at 400°C.

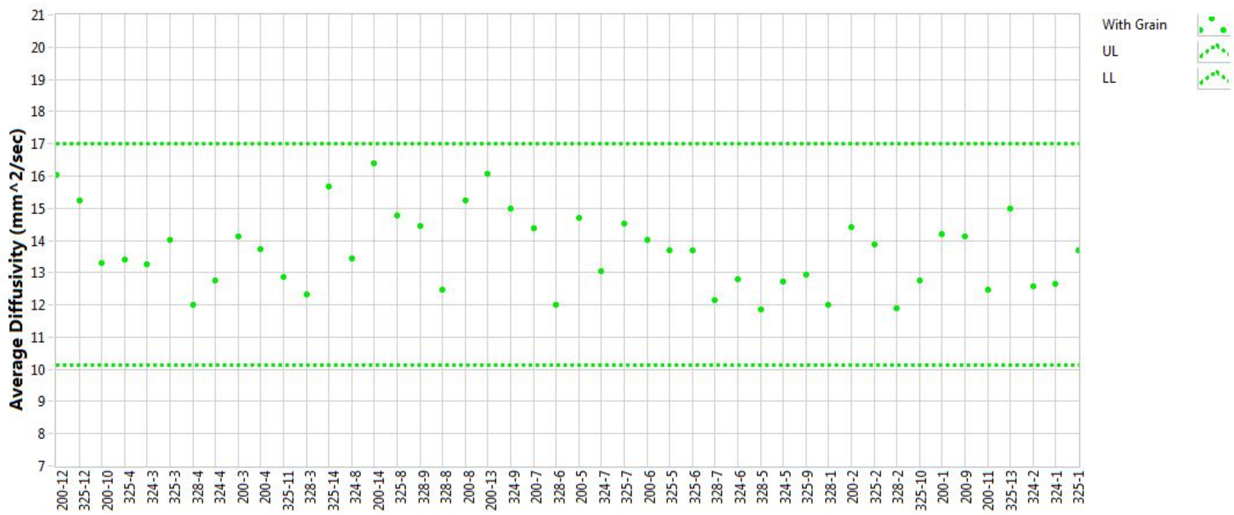

Figure A-98. GrafTech piggyback diffusivity at 400°C.

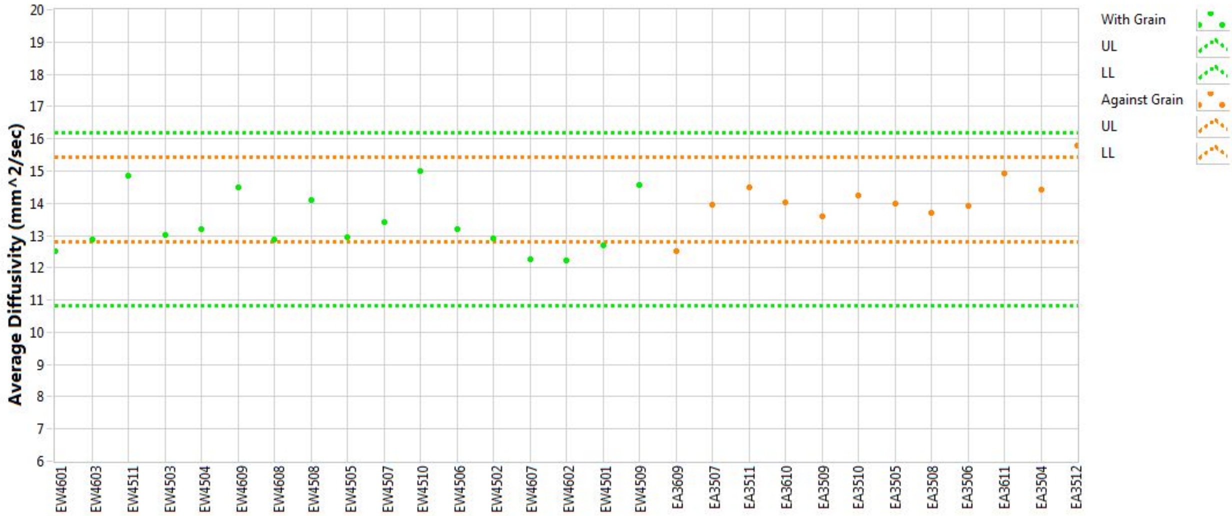

Figure A-99. IG-110 piggyback diffusivity at 400°C.

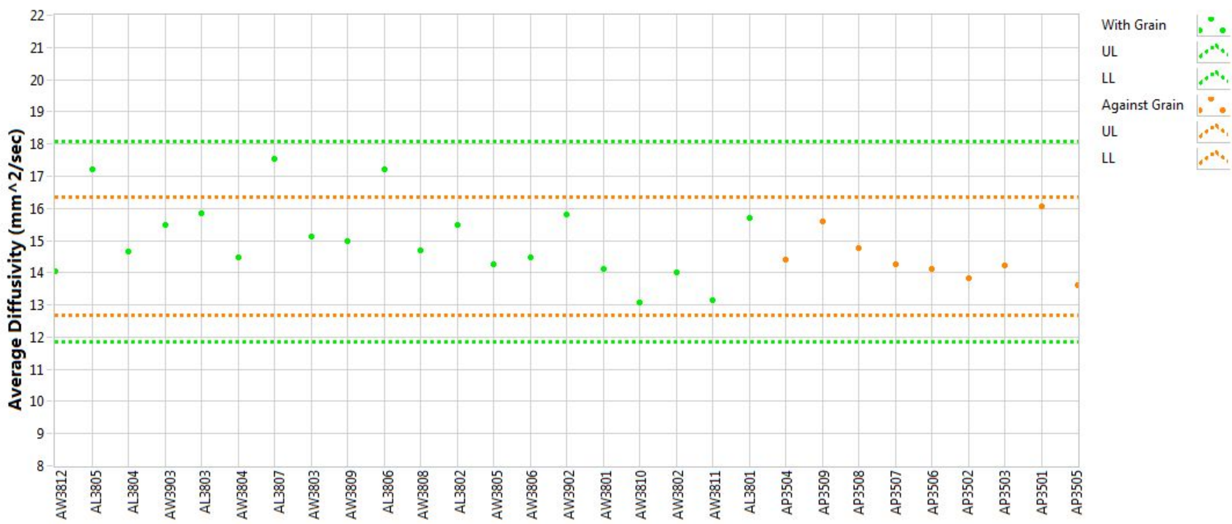

Figure A-100. NBG-17 piggyback diffusivity at 400°C.

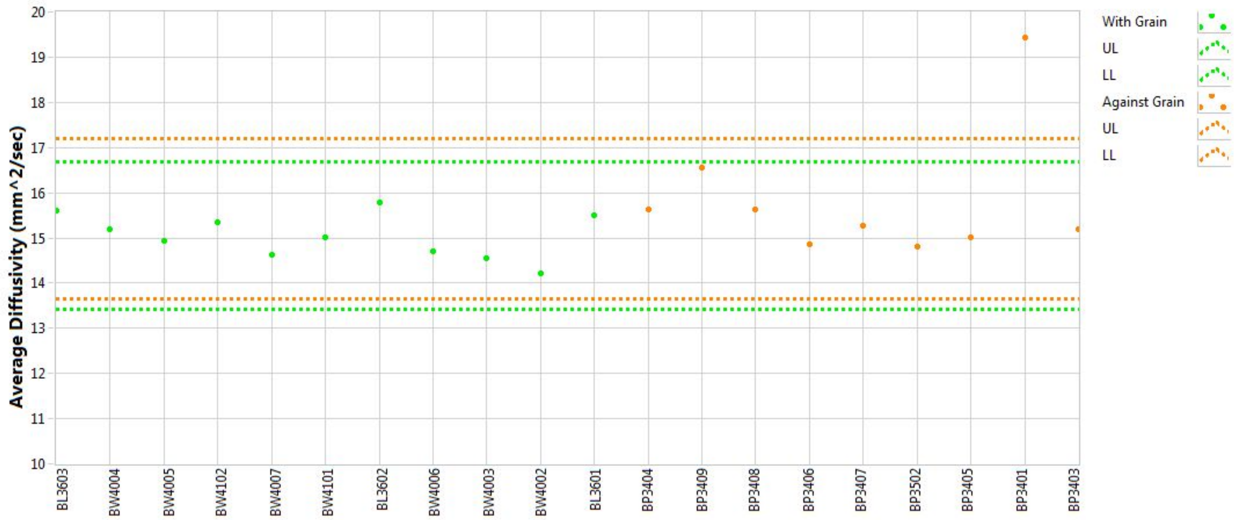

Figure A-101. NBG-18 piggyback diffusivity at 400°C.

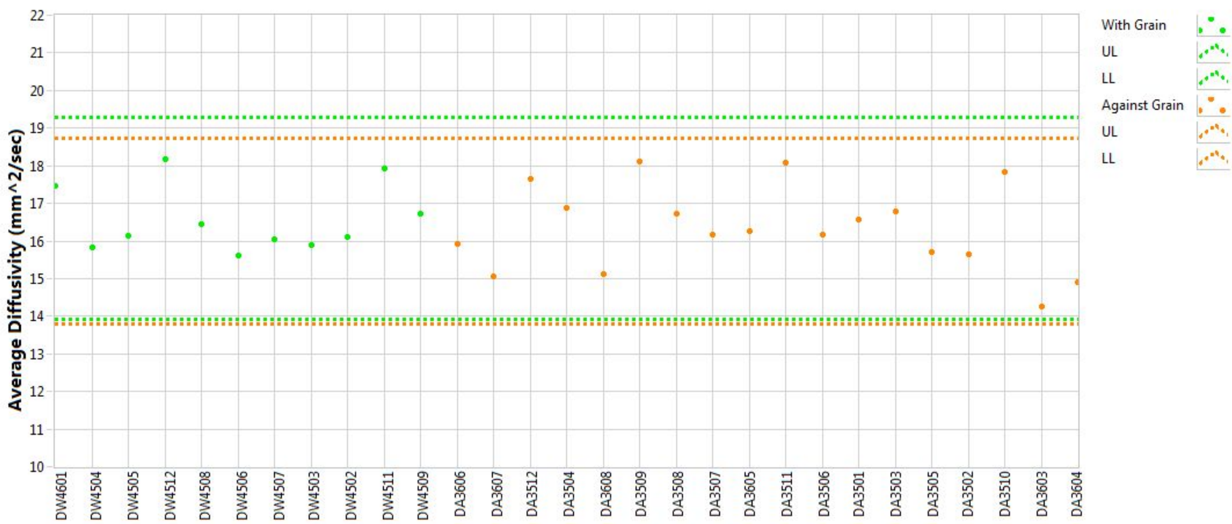

Figure A-102. PCEA piggyback diffusivity at 400°C.

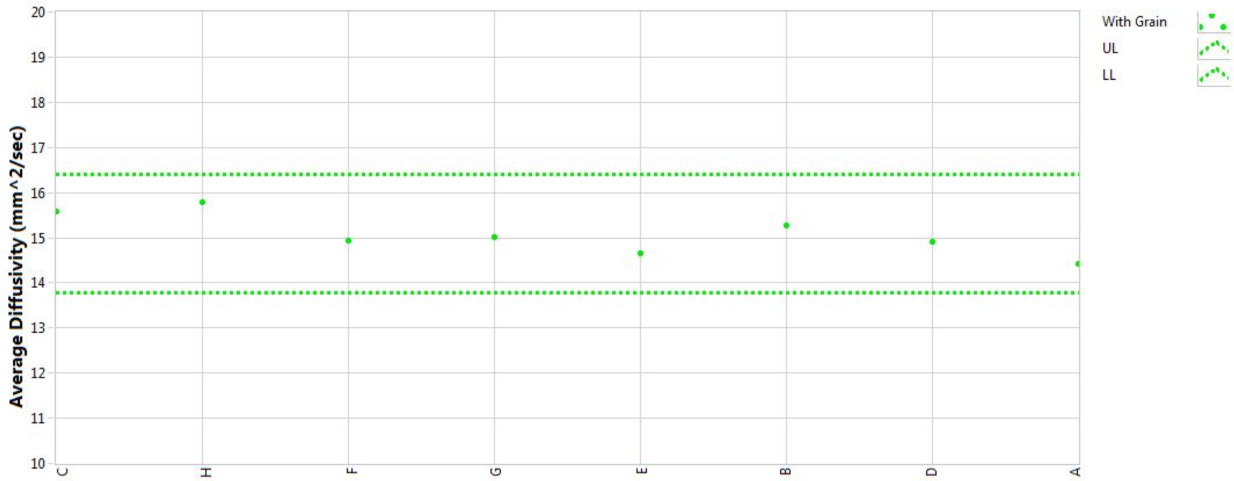

Figure A-103. SGL-SiC piggyback diffusivity at 400°C.

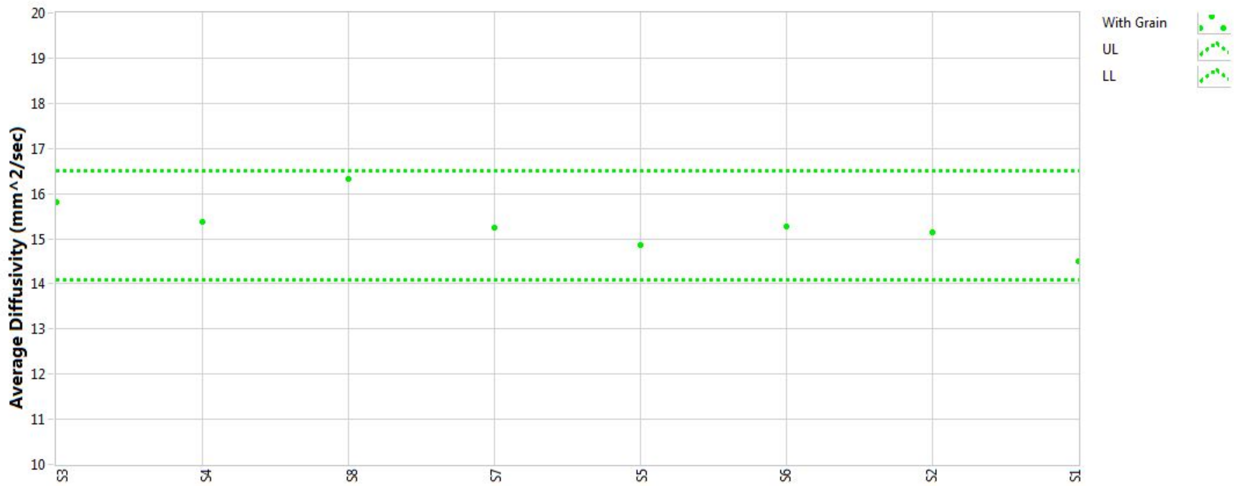

Figure A-104. SGL piggyback diffusivity at 400°C.

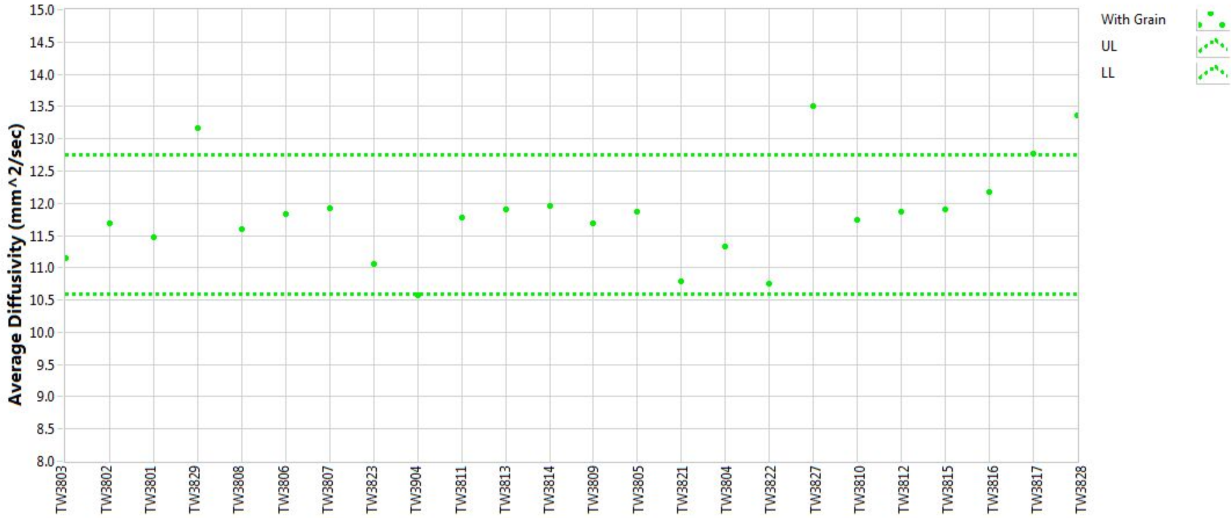

Figure A-105. 2114 piggyback diffusivity at 650°C.

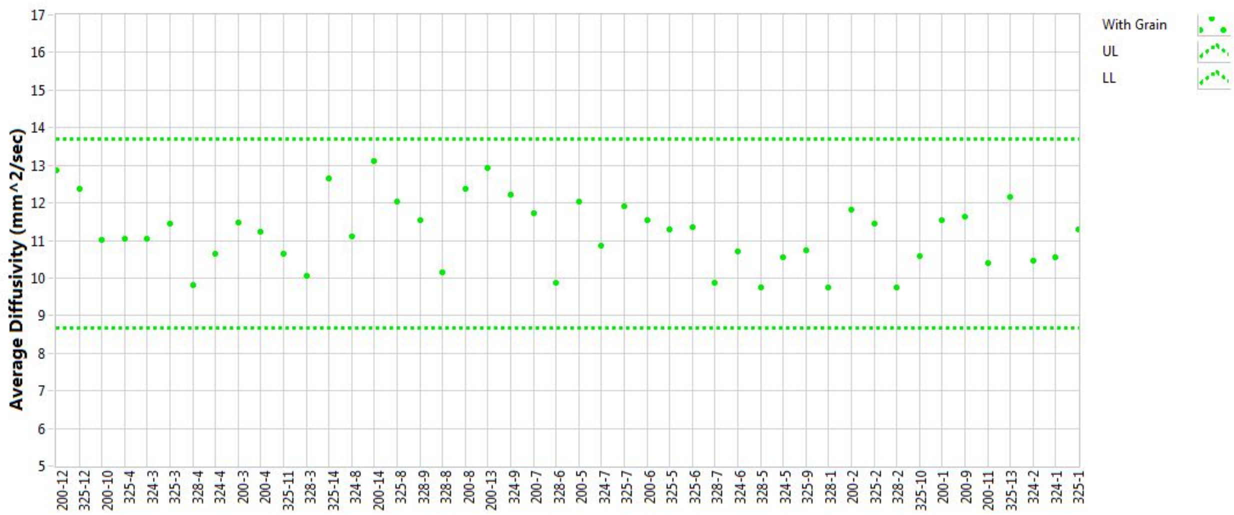

Figure A-106. GrafTech piggyback diffusivity at 650°C.

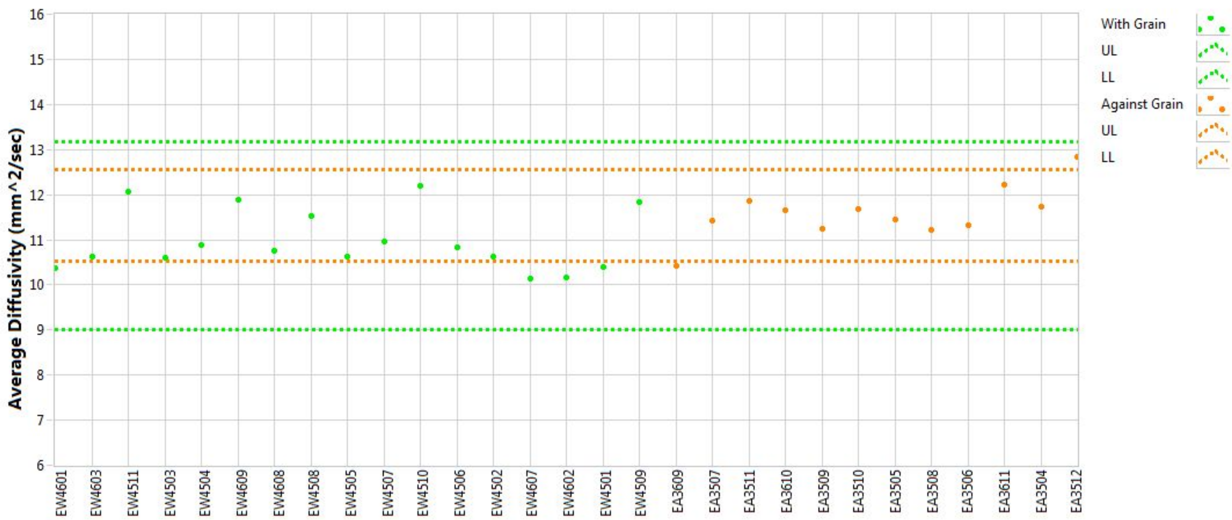

Figure A-107. IG-110 piggyback diffusivity at 650°C.

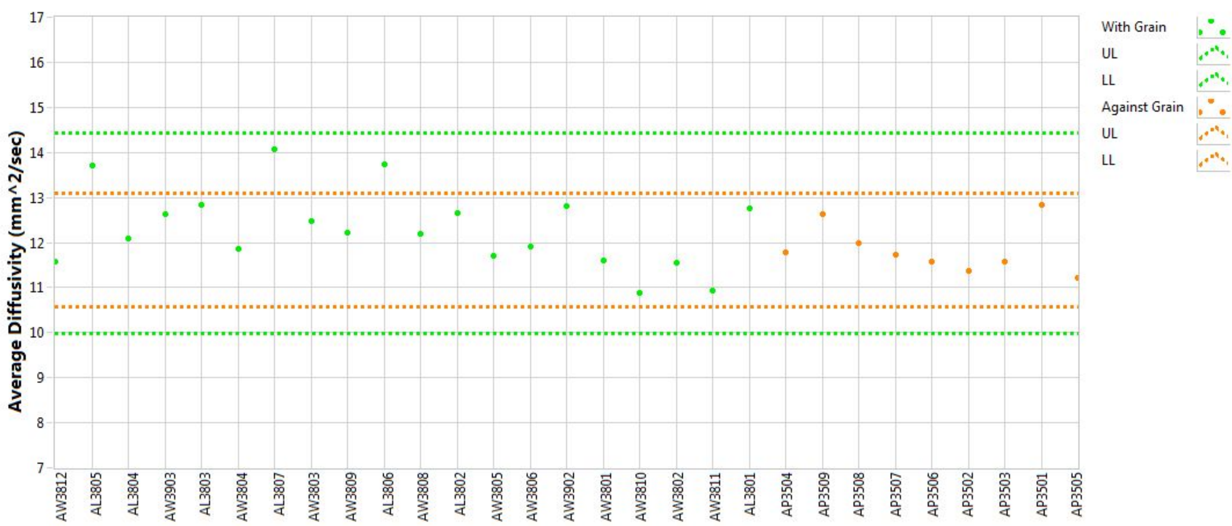

Figure A-108. NBG-17 piggyback diffusivity at 650°C.

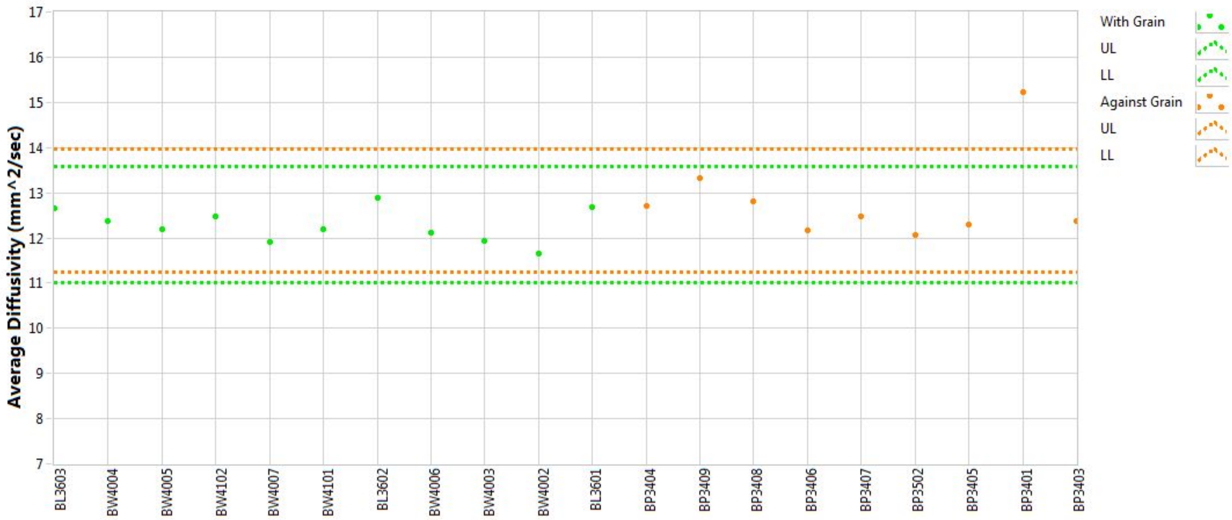

Figure A-109. NBG-18 piggyback diffusivity at 650°C.

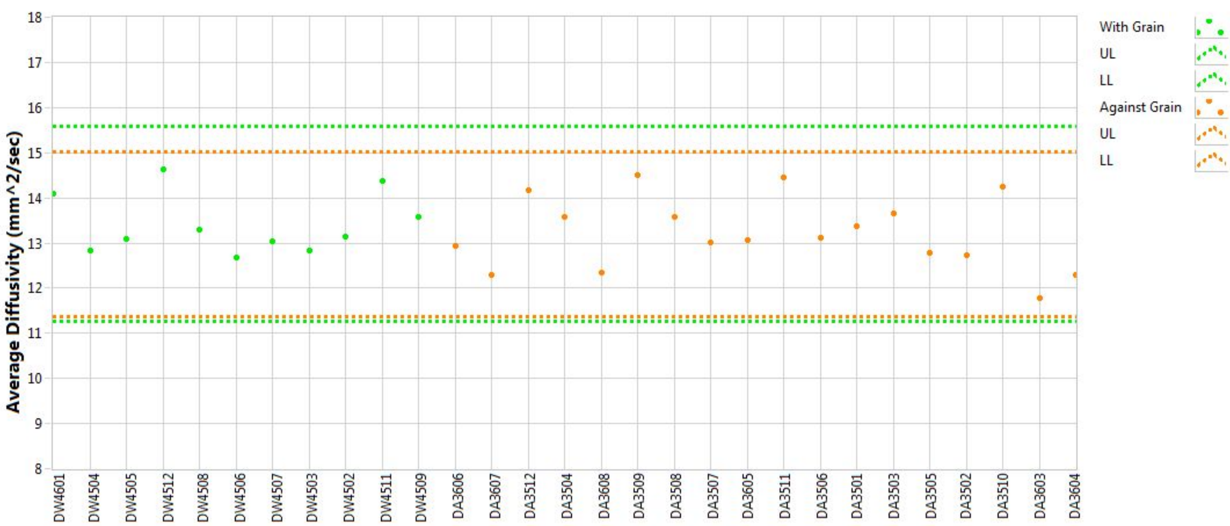

Figure A-110. PCEA piggyback diffusivity at 650°C.

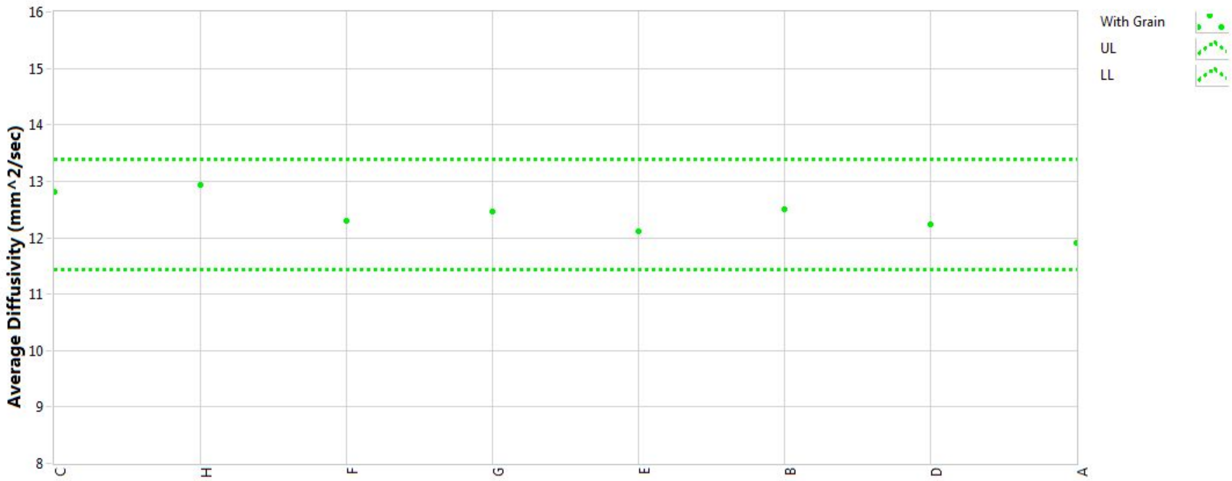

Figure A-111. SGL-SiC piggyback diffusivity at 650°C.

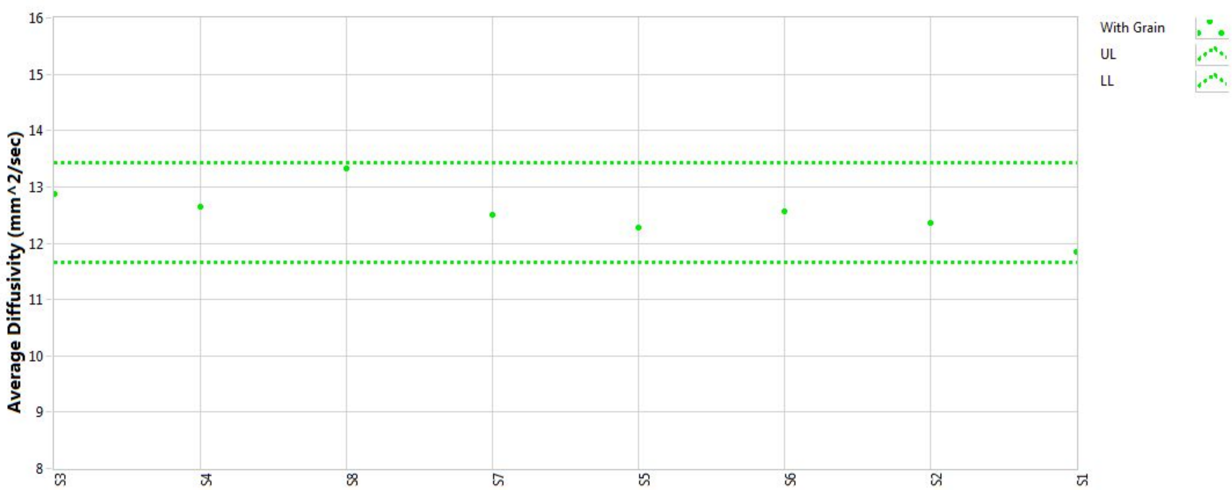

Figure A-112 SGL piggyback diffusivity at 650°C.

Appendix B

Statistical Tables

Appendix B

Statistical Tables

Table B-1. Creep specimen length (mm) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	25.172	0.176	0.70	25.272	25.742	24.585
IG-110	25.069	0.201	0.80	25.160	25.757	24.349
NBG-17	25.034	0.216	0.86	25.135	25.718	24.302
NBG-18	25.140	0.177	0.70	25.207	25.761	24.484
PCEA	25.020	0.234	0.94	25.109	25.743	24.280
Against Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114						
IG-110	24.967	0.224	0.90	25.003	25.759	24.193
NBG-17	25.056	0.229	0.92	25.163	25.728	24.282
NBG-18	25.139	0.180	0.71	25.201	25.691	24.587
PCEA	25.070	0.219	0.87	25.136	25.722	24.407
With Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114	25.172	0.176	0.70	25.272	25.742	24.585
IG-110	25.110	0.178	0.71	25.174	25.684	24.544
NBG-17	25.011	0.206	0.83	25.076	25.664	24.395
NBG-18	25.141	0.179	0.71	25.223	25.763	24.484
PCEA	25.003	0.240	0.96	25.104	25.743	24.280

Table B-2. Creep specimen diameter (mm) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	12.475	0.031	0.25	12.463	12.579	12.372
IG-110	12.460	0.035	0.28	12.462	12.579	12.337
NBG-17	12.414	0.036	0.29	12.421	12.537	12.280
NBG-18	12.456	0.034	0.27	12.455	12.572	12.347
PCEA	12.423	0.037	0.30	12.425	12.532	12.320

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	12.439	0.029	0.23	12.439	12.529	12.352
NBG-17	12.411	0.041	0.33	12.423	12.550	12.258
NBG-18	12.455	0.038	0.31	12.451	12.590	12.326
PCEA	12.421	0.037	0.30	12.426	12.508	12.344

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	12.475	0.031	0.25	12.463	12.579	12.372
IG-110	12.468	0.034	0.27	12.477	12.571	12.366
NBG-17	12.416	0.032	0.26	12.419	12.525	12.303
NBG-18	12.457	0.030	0.24	12.456	12.545	12.367
PCEA	12.424	0.037	0.30	12.424	12.534	12.318

Table B-3. Creep specimen mass (g) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.534	0.010	0.18	5.533	5.558	5.512
IG-110	5.391	0.032	0.60	5.399	5.462	5.327
NBG-17	5.549	0.018	0.33	5.543	5.603	5.497
NBG-18	5.665	0.020	0.36	5.665	5.726	5.602
PCEA	5.417	0.020	0.37	5.416	5.453	5.379

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	5.357	0.035	0.66	5.364	5.441	5.280
NBG-17	5.547	0.019	0.35	5.542	5.600	5.496
NBG-18	5.676	0.017	0.30	5.679	5.727	5.630
PCEA	5.437	0.024	0.44	5.434	5.491	5.375

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.534	0.010	0.18	5.533	5.558	5.512
IG-110	5.404	0.018	0.34	5.403	5.462	5.348
NBG-17	5.552	0.018	0.32	5.543	5.609	5.496
NBG-18	5.653	0.015	0.27	5.651	5.697	5.606
PCEA	5.411	0.014	0.25	5.413	5.450	5.372

Table B-4. Creep specimen density (g/cm^3) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.8197	0.0082	0.45	1.8196	1.8381	1.7990
IG-110	1.7976	0.0147	0.82	1.7999	1.8368	1.7540
NBG-17	1.8621	0.0193	1.04	1.8631	1.9005	1.8227
NBG-18	1.8833	0.0200	1.06	1.8853	1.9441	1.8253
PCEA	1.8148	0.0200	1.10	1.8118	1.8642	1.7594

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	1.8026	0.0176	0.98	1.8051	1.8544	1.7532
NBG-17	1.8613	0.0251	1.35	1.8597	1.9363	1.7999
NBG-18	1.8891	0.0171	0.90	1.8944	1.9333	1.8461
PCEA	1.8164	0.0271	1.49	1.8074	1.8794	1.7468

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.8197	0.0082	0.45	1.8196	1.8381	1.7990
IG-110	1.7956	0.0132	0.74	1.7948	1.8328	1.7564
NBG-17	1.8629	0.0117	0.63	1.8655	1.8939	1.8291
NBG-18	1.8774	0.0214	1.14	1.8734	1.9572	1.7935
PCEA	1.8142	0.0175	0.97	1.8141	1.8567	1.7703

Table B-5. Creep specimen coefficient of thermal expansion (1/k) summary statistics at 100°C.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.28E-06	5.23E-07	9.90	5.12E-06	7.34E-06	3.37E-06
IG-110	4.38E-06	5.28E-07	12.07	4.28E-06	5.97E-06	2.77E-06
NBG-17	4.79E-06	4.93E-07	10.29	4.81E-06	6.47E-06	3.20E-06
NBG-18	4.75E-06	4.13E-07	8.71	4.74E-06	6.14E-06	3.34E-06
PCEA	4.63E-06	5.11E-07	11.04	4.63E-06	6.25E-06	2.95E-06

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	4.13E-06	4.17E-07	10.10	4.13E-06	5.58E-06	2.62E-06
NBG-17	4.84E-06	5.12E-07	10.56	4.83E-06	6.49E-06	3.33E-06
NBG-18	4.67E-06	4.30E-07	9.22	4.75E-06	6.15E-06	3.12E-06
PCEA	4.88E-06	4.80E-07	9.85	4.86E-06	6.60E-06	3.18E-06

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.28E-06	5.23E-07	9.90	5.12E-06	7.34E-06	3.37E-06
IG-110	4.48E-06	5.40E-07	12.08	4.51E-06	6.27E-06	2.71E-06
NBG-17	4.73E-06	4.82E-07	10.17	4.68E-06	6.55E-06	3.05E-06
NBG-18	4.83E-06	3.89E-07	8.06	4.73E-06	6.03E-06	3.67E-06
PCEA	4.55E-06	5.01E-07	11.02	4.56E-06	6.24E-06	2.80E-06

Table B-6. Creep specimen coefficient of thermal expansion (1/k) summary statistics at 400°C.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.71E-06	5.52E-07	9.67	5.59E-06	7.69E-06	3.92E-06
IG-110	4.75E-06	5.38E-07	11.32	4.64E-06	6.42E-06	3.02E-06
NBG-17	5.20E-06	5.41E-07	10.40	5.31E-06	7.08E-06	3.27E-06
NBG-18	5.17E-06	4.52E-07	8.75	5.20E-06	6.72E-06	3.60E-06
PCEA	5.07E-06	5.33E-07	10.52	5.13E-06	6.83E-06	3.17E-06

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	4.45E-06	4.43E-07	9.96	4.55E-06	5.93E-06	2.85E-06
NBG-17	5.28E-06	5.53E-07	10.48	5.33E-06	7.21E-06	3.49E-06
NBG-18	5.12E-06	4.51E-07	8.81	5.17E-06	6.61E-06	3.55E-06
PCEA	5.35E-06	4.85E-07	9.06	5.33E-06	7.09E-06	3.67E-06

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.71E-06	5.52E-07	9.67	5.59E-06	7.69E-06	3.92E-06
IG-110	4.87E-06	5.30E-07	10.89	4.94E-06	6.75E-06	2.99E-06
NBG-17	5.12E-06	5.31E-07	10.37	5.01E-06	6.93E-06	3.24E-06
NBG-18	5.23E-06	4.57E-07	8.75	5.21E-06	6.62E-06	3.80E-06
PCEA	4.98E-06	5.21E-07	10.48	4.99E-06	6.62E-06	3.24E-06

Table B-7. Creep specimen coefficient of thermal expansion (1/k) summary statistics at 650°C.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	6.05E-06	5.63E-07	9.29	5.90E-06	8.05E-06	4.25E-06
IG-110	5.20E-06	5.64E-07	10.84	5.07E-06	6.79E-06	3.55E-06
NBG-17	5.54E-06	5.57E-07	10.06	5.61E-06	7.56E-06	3.48E-06
NBG-18	5.52E-06	4.81E-07	8.73	5.54E-06	7.22E-06	3.74E-06
PCEA	5.45E-06	5.62E-07	10.30	5.48E-06	7.28E-06	3.50E-06

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	4.89E-06	4.72E-07	9.66	5.00E-06	6.33E-06	3.37E-06
NBG-17	5.62E-06	5.67E-07	10.09	5.69E-06	7.55E-06	3.91E-06
NBG-18	5.47E-06	4.73E-07	8.65	5.50E-06	7.03E-06	3.83E-06
PCEA	5.72E-06	5.04E-07	8.81	5.69E-06	7.51E-06	3.99E-06

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	6.05E-06	5.63E-07	9.29	5.90E-06	8.05E-06	4.25E-06
IG-110	5.33E-06	5.55E-07	10.41	5.40E-06	7.48E-06	3.24E-06
NBG-17	5.45E-06	5.50E-07	10.09	5.34E-06	7.28E-06	3.55E-06
NBG-18	5.57E-06	4.95E-07	8.89	5.61E-06	7.01E-06	4.11E-06
PCEA	5.36E-06	5.57E-07	10.38	5.33E-06	7.17E-06	3.47E-06

Table B-8. Creep specimen Young's modulus (GPa) by sonic resonance summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	17.11	0.50	2.94	17.07	18.47	15.72
IG-110	16.83	0.68	4.04	16.82	18.76	14.88
NBG-17	16.97	0.80	4.74	16.93	19.50	14.34
NBG-18	17.89	0.77	4.31	17.81	19.63	16.16
PCEA	14.58	0.86	5.90	14.89	17.30	11.66

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	17.40	0.71	4.09	17.44	18.97	15.47
NBG-17	16.84	0.95	5.66	16.53	19.71	14.13
NBG-18	18.16	0.65	3.58	17.89	20.06	16.28
PCEA	15.34	0.48	3.13	15.23	16.45	14.17

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	17.11	0.50	2.94	17.07	18.47	15.72
IG-110	16.60	0.52	3.14	16.61	18.28	14.94
NBG-17	17.10	0.62	3.64	17.18	19.00	15.10
NBG-18	17.62	0.80	4.56	17.50	19.18	15.92
PCEA	14.33	0.81	5.65	14.45	17.12	11.38

Table B-9. Creep specimen resistivity (μΩ-m) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	24.83	0.70	2.80	24.58	26.20	23.28
IG-110	26.04	0.93	3.57	26.12	28.86	23.29
NBG-17	24.92	0.67	2.70	24.84	26.80	23.13
NBG-18	23.82	0.62	2.59	23.73	25.66	21.93
PCEA	23.58	0.75	3.18	23.49	25.48	21.69

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	25.46	0.84	3.30	25.30	28.11	22.74
NBG-17	24.99	0.61	2.42	24.92	26.48	23.55
NBG-18	23.58	0.59	2.50	23.56	25.16	21.99
PCEA	23.39	0.75	3.22	23.10	24.08	22.21

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	24.83	0.70	2.80	24.58	26.20	23.28
IG-110	26.29	0.86	3.29	26.47	29.08	23.52
NBG-17	24.85	0.74	2.98	24.64	26.83	23.09
NBG-18	24.07	0.55	2.30	24.06	25.72	22.45
PCEA	23.66	0.75	3.17	23.70	25.25	22.08

Table B-10. Creep specimen Young's modulus (GPa) by sonic velocity summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	19.72	0.53	2.71	19.69	20.99	18.32
IG-110	18.63	0.95	5.08	18.52	21.38	15.83
NBG-17	20.22	0.96	4.73	20.13	23.23	17.12
NBG-18	21.60	1.06	4.92	21.63	24.29	18.86
PCEA	18.27	0.77	4.21	18.20	20.94	15.65

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
IG-110	19.50	0.75	3.85	19.60	21.66	17.17
NBG-17	19.98	1.05	5.27	19.62	21.74	17.75
NBG-18	21.94	0.88	4.03	21.87	25.05	18.69
PCEA	18.11	0.69	3.83	18.11	20.61	15.60

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	19.72	0.53	2.71	19.69	20.99	18.32
IG-110	18.23	0.74	4.06	18.08	20.53	15.84
NBG-17	20.47	0.81	3.96	20.72	23.04	17.60
NBG-18	21.27	1.14	5.36	20.98	24.21	18.09
PCEA	18.34	0.80	4.34	18.20	20.94	15.88

Table B-11. Creep specimen shear modulus (GPa) by sonic velocity summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	7.12	0.22	3.10	7.14	7.77	6.46
IG-110	7.42	0.31	4.23	7.39	8.44	6.48
NBG-17	7.35	0.24	3.29	7.31	7.89	6.77
NBG-18	7.67	0.31	4.10	7.70	8.42	6.86
PCEA	6.93	0.17	2.47	6.92	7.33	6.49
Against Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114						
IG-110	7.58	0.30	4.00	7.49	8.78	6.44
NBG-17	7.33	0.30	4.12	7.26	8.19	6.39
NBG-18	7.75	0.32	4.10	7.71	8.44	7.17
PCEA	6.95	0.22	3.10	6.95	7.44	6.40
With Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114	7.12	0.22	3.10	7.14	7.77	6.46
IG-110	7.35	0.30	4.05	7.29	8.27	6.47
NBG-17	7.37	0.17	2.33	7.34	7.71	7.00
NBG-18	7.60	0.30	3.94	7.67	8.56	6.63
PCEA	6.92	0.15	2.23	6.90	7.31	6.51

Table B-12. Piggyback specimen length (mm) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	6.306	0.012	0.18	6.304	6.336	6.271
GrafTech	6.315	0.016	0.25	6.315	6.371	6.259
IG-110	6.242	0.017	0.27	6.241	6.290	6.189
NBG-17	6.284	0.021	0.34	6.277	6.355	6.212
NBG-18	6.295	0.023	0.36	6.296	6.359	6.227
PCEA	6.132	0.862	14.05	6.282	6.391	6.196
PCIB	6.303	0.003	0.05	6.301	6.311	6.295
SGL-SiC	6.375	0.015	0.24	6.375	6.403	6.341
SGL	6.295	0.017	0.28	6.290	6.329	6.256

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
GrafTech						
IG-110	6.247	0.019	0.30	6.247	6.287	6.197
NBG-17	6.284	0.023	0.37	6.272	6.361	6.209
NBG-18	6.285	0.022	0.34	6.280	6.329	6.239
PCEA	6.046	1.084	17.92	6.284	6.400	6.193
PCIB						
SGL-SiC						
SGL						

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	6.306	0.012	0.18	6.304	6.336	6.271
GrafTech	6.315	0.016	0.25	6.315	6.371	6.259
IG-110	6.239	0.015	0.24	6.241	6.291	6.187
NBG-17	6.283	0.021	0.33	6.282	6.356	6.211
NBG-18	6.304	0.020	0.32	6.305	6.340	6.268
PCEA	6.279	0.031	0.49	6.280	6.383	6.168
PCIB	6.303	0.003	0.05	6.301	6.311	6.295
SGL-SiC	6.375	0.015	0.24	6.375	6.403	6.341
SGL	6.295	0.017	0.28	6.290	6.329	6.256

Table B-13. Piggyback specimen diameter (mm) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	12.454	0.012	0.10	12.454	12.498	12.407
GrafTech	12.425	0.054	0.44	12.416	12.604	12.242
IG-110	12.405	0.032	0.26	12.398	12.518	12.294
NBG-17	12.392	0.045	0.36	12.384	12.575	12.219
NBG-18	12.430	0.038	0.31	12.421	12.556	12.297
PCEA	11.988	2.265	18.89	12.389	12.606	12.200
PCIB	12.436	0.003	0.02	12.438	12.443	12.428
SGL-SiC	12.535	0.022	0.18	12.537	12.595	12.479
SGL	12.390	0.033	0.27	12.384	12.497	12.279

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
GrafTech						
IG-110	12.404	0.031	0.25	12.398	12.502	12.308
NBG-17	12.377	0.043	0.35	12.361	12.526	12.233
NBG-18	12.426	0.032	0.26	12.417	12.525	12.322
PCEA	11.743	2.844	24.22	12.378	12.578	12.210
PCIB						
SGL-SiC						
SGL						

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	12.454	0.012	0.10	12.454	12.498	12.407
GrafTech	12.425	0.054	0.44	12.416	12.604	12.242
IG-110	12.406	0.033	0.27	12.392	12.519	12.294
NBG-17	12.399	0.045	0.36	12.408	12.572	12.232
NBG-18	12.434	0.044	0.36	12.425	12.612	12.257
PCEA	12.411	0.055	0.44	12.404	12.635	12.188
PCIB	12.436	0.003	0.02	12.438	12.443	12.428
SGL-SiC	12.535	0.022	0.18	12.537	12.595	12.479
SGL	12.390	0.033	0.27	12.384	12.497	12.279

Table B-14. Piggyback specimen mass (g) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.408	0.003	0.181	1.407	1.413	1.402
GrafTech	1.389	0.036	2.599	1.386	1.498	1.302
IG-110	1.352	0.007	0.497	1.354	1.363	1.344
NBG-17	1.407	0.005	0.325	1.408	1.422	1.392
NBG-18	1.430	0.006	0.445	1.431	1.444	1.417
PCEA	1.333	0.252	18.908	1.376	1.395	1.360
PCIB	1.412	0.004	0.275	1.411	1.423	1.400
SGL-SiC	1.462	0.010	0.679	1.461	1.485	1.440
SGL	1.407	0.005	0.324	1.408	1.418	1.395

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
GrafTech						
IG-110	1.347	0.008	0.613	1.348	1.375	1.318
NBG-17	1.404	0.005	0.372	1.407	1.424	1.383
NBG-18	1.430	0.005	0.379	1.428	1.445	1.416
PCEA	1.310	0.318	24.237	1.377	1.404	1.355
PCIB						
SGL-SiC						
SGL						

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.408	0.003	0.181	1.407	1.413	1.402
GrafTech	1.389	0.036	2.599	1.386	1.498	1.302
IG-110	1.355	0.002	0.160	1.355	1.359	1.350
NBG-17	1.408	0.004	0.278	1.410	1.422	1.392
NBG-18	1.430	0.007	0.511	1.432	1.439	1.425
PCEA	1.373	0.006	0.442	1.375	1.394	1.353
PCIB	1.412	0.004	0.275	1.411	1.423	1.400
SGL-SiC	1.462	0.010	0.679	1.461	1.485	1.440
SGL	1.407	0.005	0.324	1.408	1.418	1.395

Table B-15. Piggyback specimen density (g/cm^3) summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.8224	0.0051	0.28	1.8232	1.8401	1.8053
GrafTech	1.8055	0.0580	3.21	1.8187	1.9013	1.7401
IG-110	1.8281	0.0564	3.09	1.8531	1.9096	1.7900
NBG-17	1.8474	0.0195	1.05	1.8514	1.9223	1.7707
NBG-18	1.8322	0.0152	0.83	1.8322	1.8778	1.7884
PCEA	1.7819	0.3373	18.93	1.8460	1.9317	1.7509
PCIB	1.8285	0.0022	0.12	1.8280	1.8352	1.8220
SGL-SiC	1.8912	0.0466	2.47	1.9092	1.9426	1.8666
SGL	1.8443	0.0131	0.71	1.8456	1.8768	1.8184
Against Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114						
GrafTech						
IG-110	1.7882	0.0698	3.91	1.7867	2.0540	1.5270
NBG-17	1.8515	0.0196	1.06	1.8604	1.9246	1.7755
NBG-18	1.8369	0.0149	0.81	1.8401	1.8759	1.7987
PCEA	1.7465	0.4235	24.25	1.8459	1.9251	1.7554
PCIB						
SGL-SiC						
SGL						
With Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114	1.8224	0.0051	0.28	1.8232	1.8401	1.8053
GrafTech	1.8055	0.0580	3.21	1.8187	1.9013	1.7401
IG-110	1.8562	0.0138	0.74	1.8602	1.9024	1.8082
NBG-17	1.8456	0.0197	1.07	1.8425	1.9181	1.7704
NBG-18	1.8283	0.0149	0.82	1.8315	1.8751	1.7854
PCEA	1.8432	0.0255	1.38	1.8460	1.9447	1.7454
PCIB	1.8285	0.0022	0.12	1.8280	1.8352	1.8220
SGL-SiC	1.8912	0.0466	2.47	1.9092	1.9426	1.8666
SGL	1.8443	0.0131	0.71	1.8456	1.8768	1.8184

Table B-16. Piggyback specimen diffusivity (mm^2/sec) at 100°C summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	21.3	2.1	9.73	20.8	23.8	18.2
GrafTech	20.5	2.2	10.68	20.2	26.7	13.7
IG-110	20.6	1.7	8.40	20.4	26.0	15.0
NBG-17	22.5	2.2	9.68	21.8	27.8	17.1
NBG-18	23.4	2.1	9.15	23.0	26.3	19.7
PCEA	25.2	2.0	7.94	24.6	29.9	20.8
PCIB	18.4	0.3	1.56	18.5	19.3	17.6
SGL-SiC	22.4	0.8	3.71	22.2	24.7	20.0
SGL	23.0	0.9	4.07	22.9	25.0	21.0

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
GrafTech						
IG-110	21.3	1.5	7.00	21.1	24.0	18.5
NBG-17	21.9	1.6	7.15	21.3	25.1	18.4
NBG-18	24.2	2.9	12.12	23.1	27.0	19.8
PCEA	25.0	2.2	8.67	24.8	29.9	19.9
PCIB						
SGL-SiC						
SGL						

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	21.3	2.1	9.73	20.8	23.8	18.2
GrafTech	20.5	2.2	10.68	20.2	26.7	13.7
IG-110	20.1	1.7	8.68	19.6	25.5	14.8
NBG-17	22.8	2.4	10.47	22.2	28.4	16.8
NBG-18	22.8	1.0	4.23	22.7	26.4	19.3
PCEA	25.5	1.7	6.85	24.6	31.2	20.2
PCIB	18.4	0.3	1.56	18.5	19.3	17.6
SGL-SiC	22.4	0.8	3.71	22.2	24.7	20.0
SGL	23.0	0.9	4.07	22.9	25.0	21.0

Table B-17. Piggyback specimen diffusivity (mm^2/sec) at 400°C summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	14.4	1.1	7.54	14.3	15.7	12.7
GrafTech	13.7	1.2	8.86	13.7	17.0	10.1
IG-110	13.7	0.9	6.74	13.7	16.7	10.6
NBG-17	14.9	1.1	7.62	14.7	17.6	12.0
NBG-18	15.4	1.1	7.04	15.2	16.8	13.7
PCEA	16.4	1.0	6.27	16.2	18.9	14.0
PCIB	12.6	0.1	1.08	12.6	13.0	12.2
SGL-SiC	15.1	0.5	3.02	15.0	16.4	13.8
SGL	15.3	0.6	3.63	15.3	16.5	14.1
Against Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114						
GrafTech						
IG-110	14.1	0.8	5.61	14.0	15.4	12.8
NBG-17	14.5	0.8	5.54	14.3	16.3	12.7
NBG-18	15.8	1.5	9.19	15.3	17.2	13.6
PCEA	16.3	1.1	6.87	16.2	18.7	13.8
PCIB						
SGL-SiC						
SGL						
With Grain Specimens	**Mean**	**Std Dev**	**CoV (%)**	**Median**	**Upper Limit**	**Lower Limit**
2114	14.4	1.1	7.54	14.3	15.7	12.7
GrafTech	13.7	1.2	8.86	13.7	17.0	10.1
IG-110	13.4	0.9	6.67	13.0	16.2	10.8
NBG-17	15.1	1.2	8.24	14.8	17.8	12.0
NBG-18	15.0	0.5	3.26	15.0	16.7	13.4
PCEA	16.6	0.9	5.33	16.1	19.3	13.9
PCIB	12.6	0.1	1.08	12.6	13.0	12.2
SGL-SiC	15.1	0.5	3.02	15.0	16.4	13.8
SGL	15.3	0.6	3.63	15.3	16.5	14.1

Table B-18. Piggyback specimen diffusivity (mm^2/sec) at 650°C summary statistics.

Combined Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	11.8	0.8	6.43	11.8	12.7	10.6
GrafTech	11.2	0.9	8.12	11.3	13.7	8.7
IG-110	11.2	0.7	6.20	11.2	13.4	9.0
NBG-17	12.2	0.8	6.58	12.0	14.2	10.0
NBG-18	12.5	0.7	5.96	12.4	13.5	11.3
PCEA	13.3	0.7	5.61	13.1	15.2	11.4
PCIB	10.5	0.0	0.26	10.5	10.5	10.4
SGL-SiC	12.4	0.3	2.77	12.4	13.4	11.4
SGL	12.6	0.4	3.47	12.5	13.4	11.7

Against Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114						
GrafTech						
IG-110	11.6	0.6	5.05	11.6	12.6	10.5
NBG-17	11.9	0.5	4.64	11.7	13.1	10.6
NBG-18	12.8	1.0	7.64	12.5	14.0	11.2
PCEA	13.2	0.8	6.02	13.1	15.0	11.4
PCIB						
SGL-SiC						
SGL						

With Grain Specimens	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	11.8	0.8	6.43	11.8	12.7	10.6
GrafTech	11.2	0.9	8.12	11.3	13.7	8.7
IG-110	11.0	0.7	6.08	10.7	13.2	9.0
NBG-17	12.3	0.9	7.05	12.2	14.3	10.1
NBG-18	12.3	0.4	3.06	12.2	13.6	11.0
PCEA	13.4	0.7	4.99	13.1	15.6	11.3
PCIB	10.5	0.0	0.26	10.5	10.5	10.4
SGL-SiC	12.4	0.3	2.77	12.4	13.4	11.4
SGL	12.6	0.4	3.47	12.5	13.4	11.7

Appendix C

Shipping Documentation for Experimental Grades

GRAFTech
International

GrafTech International Holdings Inc.
12900 Snow Road
Parma OH 44130 U.S.A.
Telephone 216.676.2445

Ship To: Idaho National Lab Attn: W. David Swank, NO P.O. or P.C. 1765 N. Yellowstone Hwy. Idaho Falls, ID 83415-2211	Special Shipping Order # 101364
Phone No: (Required) 208-526-1698	**Order Number:**
Account To Be Charged: 310910	**Shipper:** **Consignee:**
Date Issued: 1/27/12	**3rd Party:**
Ship Via: best way FEDEX 2-DAY	**Freight Charges** — **Collect:** No — **Prepaid:** Yes — **Value for Shipping:**

SHIPPING DATA	Date Shipped: 1/27/12	Kind of Containers: CTN	No. of Containers: 1	Gross Weight: 12	Net Weight:
	Prepaid Charges:	Car and Initial No.:	Signature (Shipping Dept.) [signature]		Received By:

ITEM(S) DESCRIPTION:

Graphite samples for testing:
TS 5324
TS 5328
PCIB-MG-200-45-11
PCIB-MG-325-55-11

Yes/No:	
Yes	**MSDS REQUIRED**
	MSDS ENCLOSED:
MSDS # 6033	

Requested By:
Joe Wetzel

17" X 17" X 9"

F.O. # 102747
DATE: 5/19/2011

SGL GROUP
FORWARDING ORDER

SHIPPER:

SGL GROUP
THE CARBON COMPANY
900 THERESIA ST.
ST. MARYS, PA 15857
PHONE: 781-2611

SHIP TO:

W. David Swank
Battelle Energy Alliance
[redacted]
1765 N. Yellowstone Hwy
Idaho Falls, Idaho 83415-2211

SHIP VIA: Best Way

CIRCLE: COLLECT PREPAID COD

TYPE OF SERVICE:

NEXT DAY 2 DAY 3 DAY GROUND

THE FOLLOWING GOODS:

(10) MLRF1 Pills
(18) NBG-17 SiC coated Pills
(25) NBG-17 pills
(1) Business Card

OK 5/19/11

**ECCN# **CUSTOMS VALUE

APPROVED BY EXPORT CSR:

**(ECCN# & CUSTOMS VALUE REQUIRED ON EXPORT SHIPMENTS SHIPMENTS WILL NOT BE MADE WITHOUT THIS INFORMAITON)

(CSR MUST SIGN OFF)

PERSON(S) REQUESTING SHIPMENT:

Steve Wendel

FORWARDING ORDER MUST BE MADE OUT IN TRIPLICATE (MAKE SURE ALL COPIES ARE LEGIBLE). A COPY WILL BE RETURNED TO ORIGINATOR AS PROOF OF SHIPMENT.

SHIPPING DEPT. USE ONLY:

SHIPPING UNITS: 1 ctn
NET WEIGHT: 1#
GROSS WEIGHT:
DIMENSIONS:

WHITE (SHIPPING COPY)
YELLOW (ORIGINATOR)
BLUE (PACK SLIP)

REV. 09/10/08

FORM: STM-WI-7.5.5-400-F1