INL/MIS-17-42401-Revision-0

Baseline Characterization Database Verification Report NBG-18 Billet 635-4

David Rohrbaugh

July 2017

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/MIS-17-42401-Revision-0

Baseline Characterization Database Verification Report NBG-18 Billet 635-4

David Rohrbaugh

July 2017

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy

Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Title: Baseline Characterization Database Verification Report – NBG-18 Billet 635-4

ECAR No.: 3726 Rev. No.: 0 Project No.: 32138 Date: 07/12/2017

Engineering Calculations and Analysis

Performer:	David Rohrbaugh	D520	(Signature)	7/10/2017 (Date)
Checker[1]:	W. David Swank	B120	(Signature)	7/11/17 (Date)
Independent Peer Reviewer[2]:	N/A			
CUI Reviewer: Yes ☐ or No[5] ☒	N/A			
Manager[3]:	Scott McBride	D520	(Signature)	7.10.17 (Date)
Owner[4]:	William Windes	B120	(Signature)	7-11-17 (Date)
Nuclear Safety[4]:	N/A			
Cognizant Engineer[4]:	N/A			
Quality Assurance:	Michelle Sharp	H330	(Signature)	7-11-17 (Date)

1. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.
2. Concurrence of method or approach. See definition in LWP-10106.
3. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.
4. Concurrence with the document's assumptions and input information. See definition of acceptance in LWP-10200.
5. Does the document contain CUI material? Please check either yes or no.

Title: Baseline Characterization Database Verification Report – NBG-18 Billet 635-4

ECAR No.: 3677 Rev. No.: 0 Project No.: 32138 Date: 07/12/2017

REVISION LOG

Rev.	Date	Affected Pages	Revision Description
0	07/12/2017	All	Newly issued document.

Title: Baseline Characterization Database Verification Report – NBG-18 Billet 635-4

ECAR No.: 3677 Rev. No.: 0 Project No.: 32138 Date: 07/12/2017

1. Quality Level (QL) No.	NA	**Professional Engineer's Stamp** **NA**
2. QL Determination No.	NA	
3. Engineering Job (EJ) No.	NA	
4. SSC ID	NA	
5. Building	IRC	
6. Site Area	REC	

7. Objective/Purpose:
   The purpose of this engineering calculations and analysis report is to present the data being collected in the Baseline Graphite Characterization Program, which is directly tasked with supporting Idaho National Laboratory's (INL's) research and development efforts on the Advanced Reactor Technologies (ART) Program. This program is populating a comprehensive database that will reflect the baseline properties of nuclear-grade graphite with regard to individual grade, billet, and position within individual billets. The physical and mechanical property information being collected will be transferred to the Nuclear Data Management and Analysis System (NDMAS) and that database will help populate the handbook of property data available to member nations of the Generation IV International Forum.

   Transfer of these data from the applicable technical lead to the dissemination databases available to other end users requires a full review of the test procedures and data collection efforts through an analysis of the multiple summary spreadsheets and values being collected. This report represents the analysis for NBG-18 billet 635-4 and facilitates release of associated data to the NDMAS custodians.

8. If revision, please state the reason and list sections and/or pages being affected:

   NA

9. Conclusions/Recommendations:

   Based on a review of the data spreadsheets compiled from physical and mechanical property measurements on nuclear-grade graphite billet NBG-18 635-4, no notable errors or omissions were found that will preclude the transfer of these data to the NDMAS site for storage.

   In addition to a full visual review of the data files to determine whether or not obvious errors, such as missing information, were made with the data collected, graphical representations were made of individual evaluations to provide a means to spot anomalies. The techniques employed are an adequate means of ensuring that the comprehensive amount of data collected reflect the intended values of interest. A review of the data indicates that the files, as submitted, are fully representative of the measured properties of the graphite billets being tested, as outlined in the applicable test procedures and program plans.

CONTENTS

FIGURES

PROJECT ROLES AND RESPONSIBILITIES

Project Role	Name (Typed)	Organization	Pages covered (if applicable)
Performer	David Rohrbaugh	D520	All
Checker[a]	W. David Swank	B120	All
Independent Reviewer[b]	NA		
CUI Reviewer[c]	NA		All
Manager[d]	Scott McBride	D520	
Requestor[e]	William Windes	B120	
Nuclear Safety[e]	NA		
Document Owner[e]	William Windes	B120	
Quality Assurance	Michelle Sharp	H330	

Responsibilities:

a. Confirmation of completeness, mathematical accuracy, and correctness of data and appropriateness of assumptions.

b. Concurrence of method or approach. See definition in LWP-10106.

c. Concurrence with the document’s markings in accordance with LWP-11202.

d. Concurrence of procedure compliance. Concurrence with method/approach and conclusion.

e. Concurrence with the document’s assumptions and input information. See definition of acceptance in LWP-10200.

NOTE: *Delete or mark “NA” for project roles not engaged. Include ALL personnel and their roles listed above in the eCR system. The list of the roles above is not all inclusive. If needed, the list can be extended or reduced.*

SCOPE AND BRIEF DESCRIPTION

This engineering calculations and analysis report is a validity evaluation of the physical and mechanical property databases collected on a billet of nuclear grade graphite (i.e., NBG-18 Billet 635-4) in support of the ART Baseline Graphite Characterization Program.[1,2] Millions of raw data points that have been collected during testing and quantification analyses for these billets, the summary scalar property values and supplementary traceability data are collected into comprehensive spreadsheets. Data sets are comprised of single billets of graphite for any given grade, organized by mechanical test specimen type, and further subdivided into individual spreadsheet tabs according to the specific test or evaluation being performed.

This report is not a direct analysis of properties and will not provide information on the validity or performance characteristics of the graphite itself. Rather, it is intended as a verification of the completeness of actual data collected in accordance with PLN-3467, “Baseline Graphite Characterization Plan: Electromechanical Testing,”[3] and its representation of the measurement and test results with sole regard to the graphite billets under evaluation.

DESIGN OR TECHNICAL PARAMETER INPUT AND SOURCES

Mechanical and physical property testing is carried out in accordance with PLN-3348, “Graphite Mechanical Testing,”[2] PLN-3467,[3] and PLN-3267, “AGC-2 Characterization Plan.”[4]

ASSUMPTIONS

None.

COMPUTER CODE VALIDATION

Data collection and storage is organized as reported in PLN-3467 and Idaho National Laboratory (INL)/EXT-10-19910, “Baseline Graphite Characterization: First Billet.”[5] Individual computers being used run Windows XP operating systems and store data on Microsoft Office Excel 2007 spreadsheets.

Control of individual test equipment is carried out by proprietary Netzsch software (IRC C-20) or Instron’s Bluehill (Version 2) software (load frames in IRC B-11). Both software suites are commercially available packages. Updates and data transfers/integration are handled outside of INL’s network system on a dedicated local area network.

The comprehensive interface between data collection, evaluation, and storage computers is handled through the customized LabVIEW-based Graphite Mechanical Properties Data Acquisition Software (Version 4.0). The Baseline Graphite Characterization Program’s version control and operability checks are documented and validated in a registered laboratory notebook LAB 2143, “Baseline Graphite Characterization.”[6] All pertinent lifecycle documentation is recorded in accordance with LWP-20000-01, “Conduct of Research Plan.”[7] Validation of commercial packages is handled via integrated system checks specific to each new element or upgrade as appropriate.

DISCUSSION/ANALYSIS

Introduction

The ART Project Graphite Research and Development Program is generating the extensive amount of quantitative data necessary for predicting the behavior and operating performance of the available nuclear graphite grades. To determine in-service behavior of graphite for the latest proposed designs, two main programs are underway. The first, the Advanced Graphite Creep (AGC) Program, provides a set of tests that are designed to evaluate the irradiated properties and behavior of nuclear-grade graphite over a large spectrum of conditions based on the operating environment of the very high-temperature reactor core.[1] A limited amount of data can be generated on irradiated material because of the limited availability of space within the Advanced Test Reactor and the geometric constraints placed on the AGC specimens that will be inserted. To supplement the AGC data set, the Baseline Graphite Characterization Program provides additional data that will characterize inherent property variability in nuclear-grade graphite without the testing constraints of the AGC Program.[2] This variability in properties is a natural artifact of graphite due to the geologic raw materials that are used in its production. This variability is being quantified not only within a single billet of as-produced graphite, but also from billets within a single lot, billets from different lots of the same grade, and across different billets of numerous grades of nuclear graphite that are presently available.

This particular report covers the release of physical and mechanical property data from a billet of NBG-18 graphite. The graphite billet (NBG-18 635-4) is a block of vibration-molded graphite with a large grain structure. The main baseline mechanical properties database for this billet, plots of which are included throughout this report, are comprised solely of scalar results from each of the different evaluations (i.e., mechanical testing and physical properties) in summary form, and consists of tabbed spreadsheets being occupied by over 80,000 cells of individual characteristic or property values and associated tagging information.

This report is intended as a validation review of the graphite billet NBG-18 635-4. It is not an analysis of property characteristics or trends beyond the evaluation necessary to determine if the collected data is reflective of the properties of this particular graphite billet. It is an acceptance of the test methods used, data calculations and conversions being carried out, and review of values from the standpoint of determining whether they reflect anomalous behavior that must be further investigated.

Ultimately, this report provides justification for the transfer of this data set into a storage and analysis system that is available for internal and external analysts to utilize in evaluating the relevant characteristics and performance of nuclear-grade graphite.

Database Analysis

The multitude of data sets being generated for the Baseline Graphite Characterization Program consist of properties collected on standard American Society of Testing and Materials (ASTM) international-based mechanical test specimens, as shown in Figure 1. Details of specimen tracking, traceability, process flow, and the techniques being employed to facilitate those activities is provided in detail in INL/EXT-10-19910.[5] For ease of reviewing the applicable data in this report, an example of a sectioning diagram for NBG-18 graphite along with the applicable specimen identification codes, is provided in Figure 2. This figure is representative of a single sub-block of graphite from this billet.

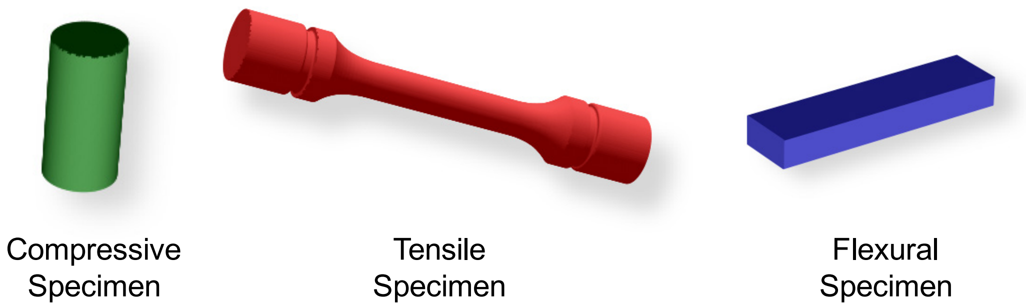


Figure 1. The three types of mechanical test specimens that will be machined from stock graphite and provide the basis for material property evaluations.

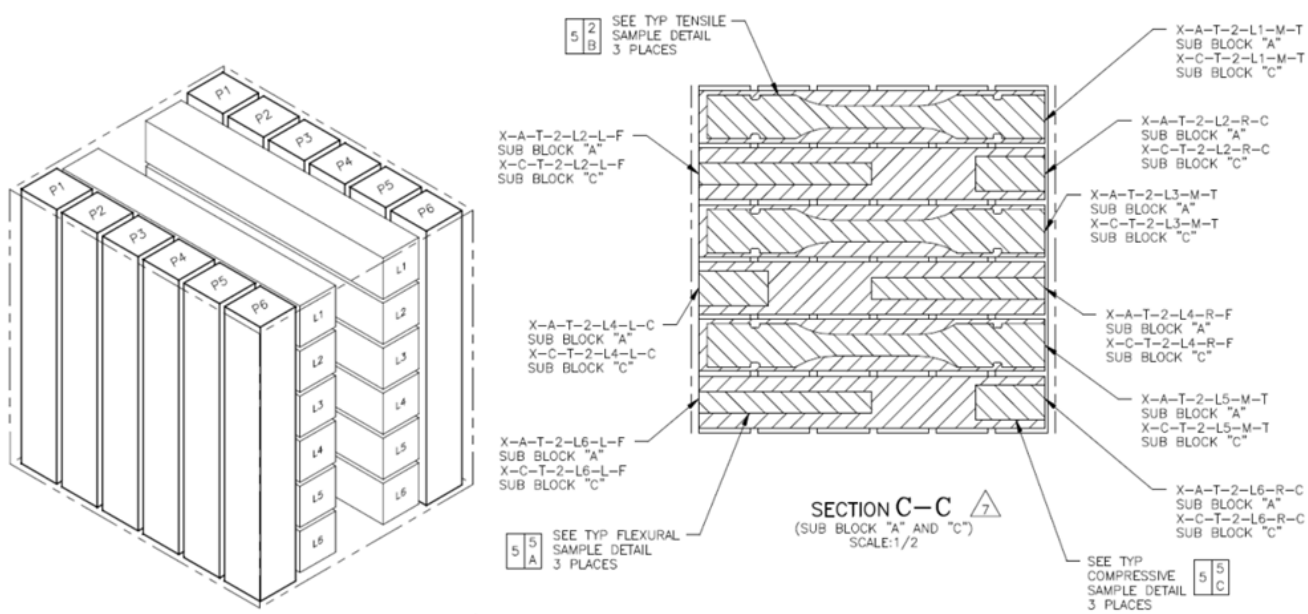


Figure 2. Individual specimen extraction and tracking identification from NBG-18 635-4.

Sections of this report cover each of the individual databases (spreadsheets) for this billet. They are divided by mechanical test specimen type (e.g., compressive, flexural, and tensile), and are organized so they present data in graphical form. The graphic representations are not sorted in any way aside from the actual order they were tested, which was randomized for the express purpose of minimizing test anomalies based on actual test timeframes. Some expectation of variation in the property values exists, but individual data points that fall within a reasonable property value range are considered acceptable. However, data that falls outside of three standard deviations from the mean does not warrant automatic exclusion from the database. These data will be subject to further scrutiny to determine whether the data are valid.

Comparisons of extreme values with other associated properties (i.e., a comparison of maximum tensile load values with measured strain to determine whether they are related by the expected elastic modulus) are also carried out where applicable. Each of these comparisons and analyses may not be explicitly included in the text of this report, but the process control charts with standard deviation values and/or property trend charts for the various characteristics being measured are included (±1, 2, and 3 standard deviations are represented by the yellow, orange, and red dotted lines and the mean is represented by the green line).

One of the clear goals of the Baseline Graphite Characterization Program is to identify and quantify inter-billet variation. However, the focus of this analysis is to compare values from complete data sets to quickly identify outlying points. One example would be a "zero" value for a specific property—quickly identifiable on a test result trend graph—providing an indication that the specific spreadsheet cell is improperly empty. Another example would be a large disparity between a limited number of points on that same test result trend graph that result from missing values in other cells (i.e., dimensional measurements from which final properties are calculated). This verification will couple those observations with a comprehensive data scan of individual points to determine whether the data set can be considered complete and the scalar summary points provided to the NDMAS are appropriately representative of the billet under evaluation.

Compression Specimen Database (NBG-18 635-4C)

Compression Testing

Compression testing was performed per ASTM C695-15[8] and PLN-3467. Figure 3 shows the maximum applied load for each of the 262 compression specimens from Billet 635-4. As was mentioned previously, some variation in graphite properties is expected, and this variation is reflected in the difference in test frame loading. The compressive strength values (Figure 4) correlate directly with the recorded load values, confirming the stress calculations were performed correctly. An additional check of critical property values is the measured deflection (Figure 5) of the loading surface, or upper platen, as measured by a calibrated deflectometer. Within geometric variations, the deflection should reflect the calculated compressive strain as shown in Figure 6.

Three specimens had compressive strengths less than 3 standard deviations from the mean (see Figure 4). However, these same specimens also had relatively low strain. Figure 6 indicates a similar material modulus. Dimensional input values have been checked and no anomalies were found. As explained above this testing not only strives to provide a scalar mean value for the measured property but also strives to establish the property variability. The mere fact that a value falls outside of 3 standard deviations is not reason enough to exclude it from this or future analysis of the data. In this case and others below, the values falling outside 3 standard deviations only trigger a closer look at the consistency of the values with other related measured values such as dimensions or elastic properties. This evaluation of data near or exceeding 3 standard deviations has been performed for all the properties presented here and any anomalies that were found are presented.

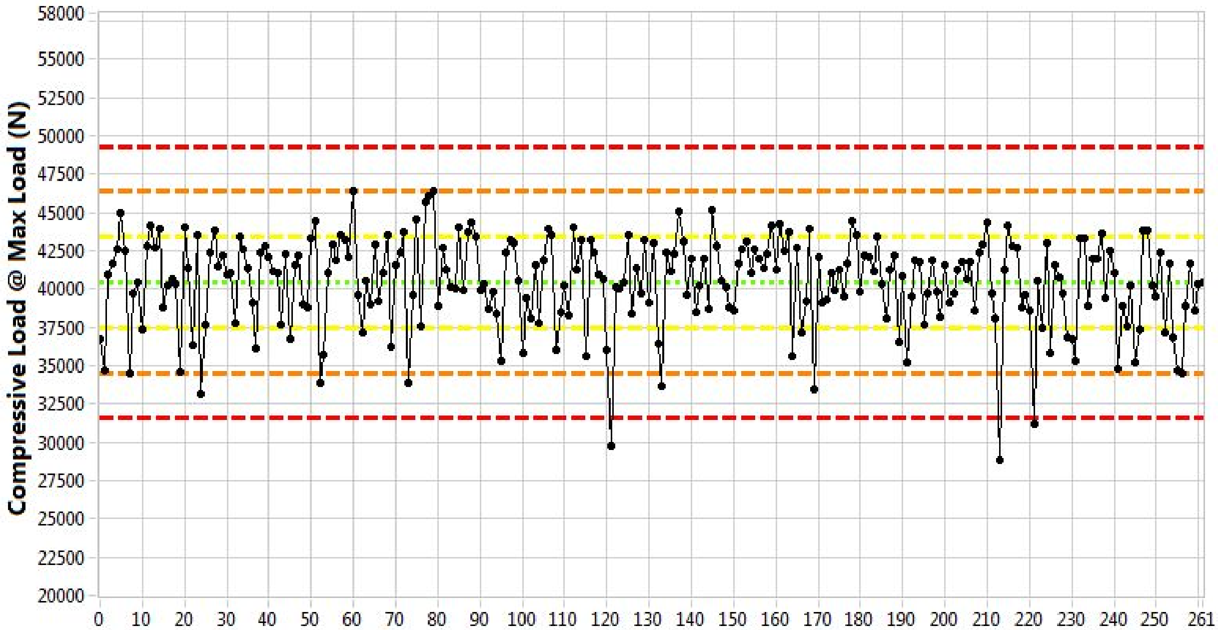


Figure 3. Compressive load at max load (N), mean = 40435, standard deviation = 2955.

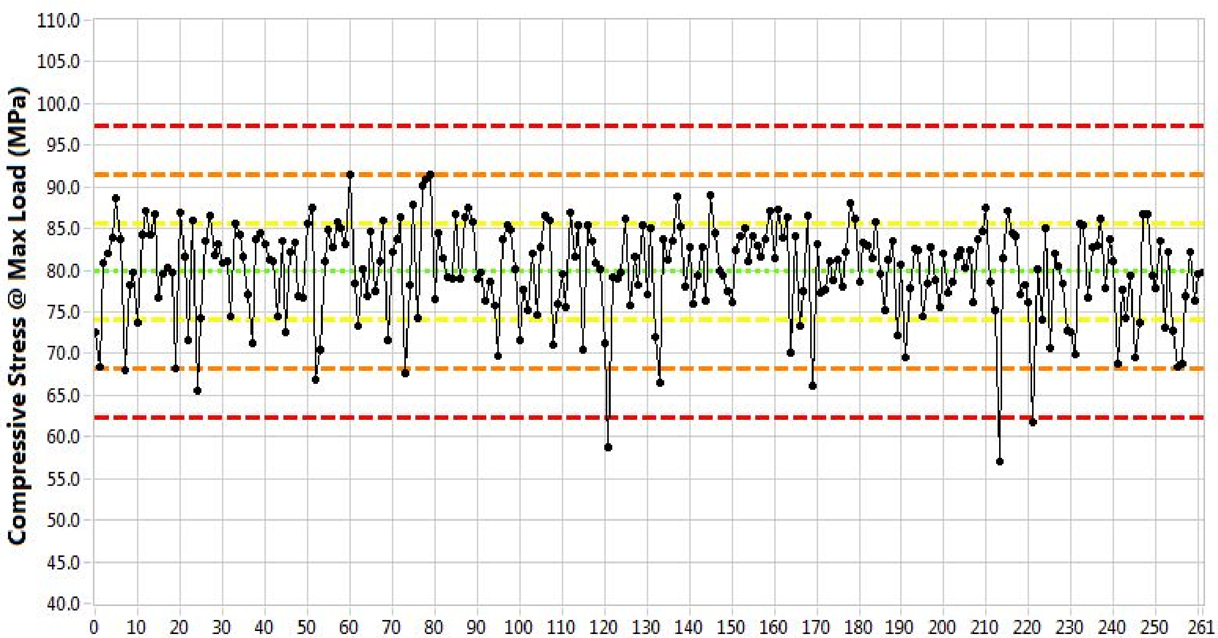


Figure 4. Compressive stress at max load (MPa), mean = 79.8, standard deviation = 5.8.

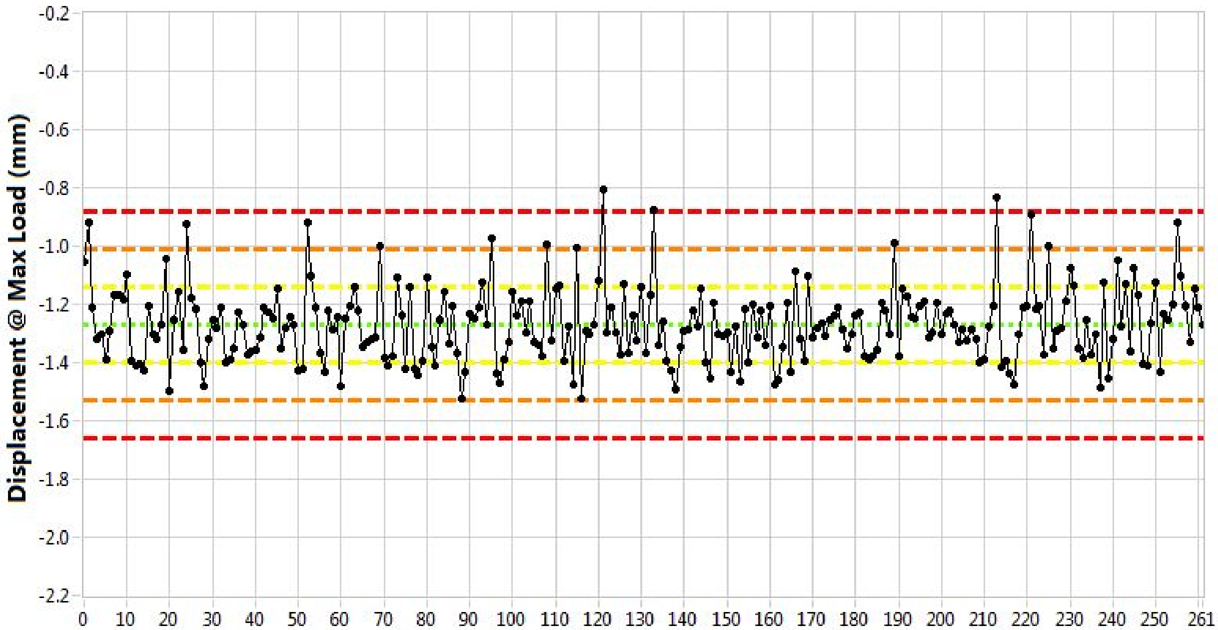


Figure 5. Displacement at max load (mm), mean = -1.27, standard deviation = 0.1302.

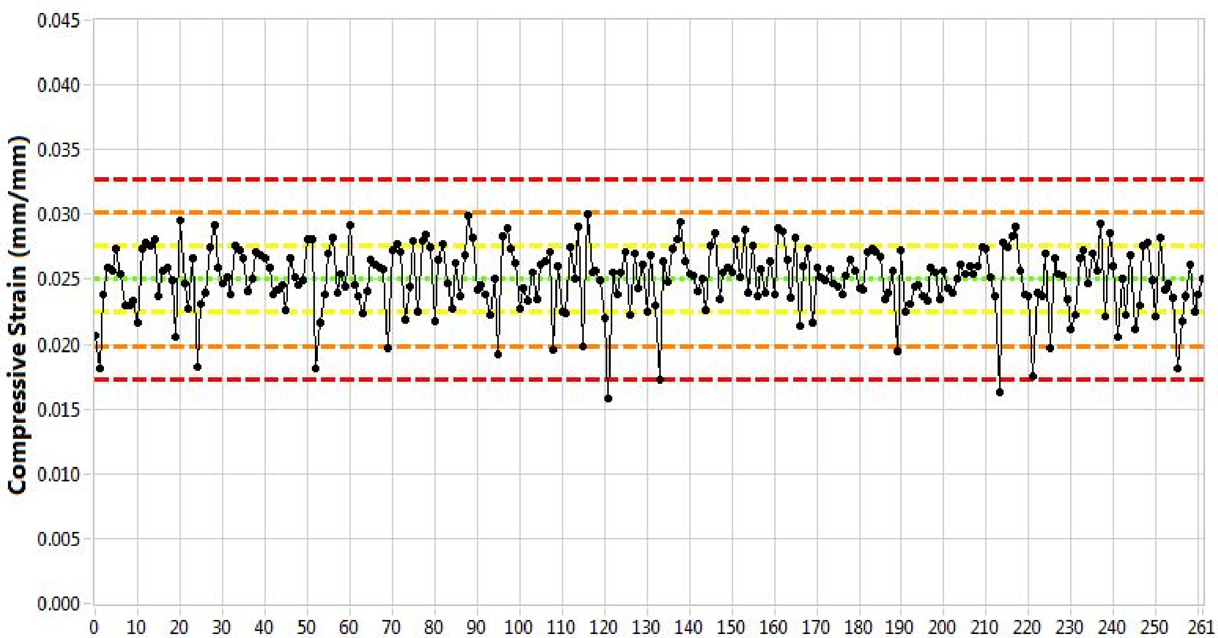
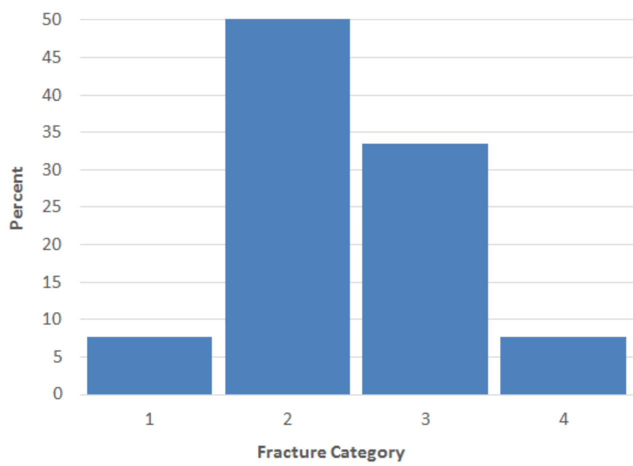


Figure 6. Compressive strain (mm/mm), mean = 0.025, standard deviation = 0.0026.

Fracture Surface Categorization

Resulting fracture surfaces from compressive specimens offer an additional opportunity to collect scalar data that can be sorted with respect to graphite type and position. To allow for consistency in what is essentially a qualitative attribute, a description of each of the fracture types is provided to the user of the Graphite Mechanical Properties Data Acquisition Software. A screen shot of this categorization, along with distribution of recorded fracture categories for each of the 262 compressive specimens from NBG-18 635-4 (with no anomalous values indicative of an unallowable characterization), is provided in Figure 7.



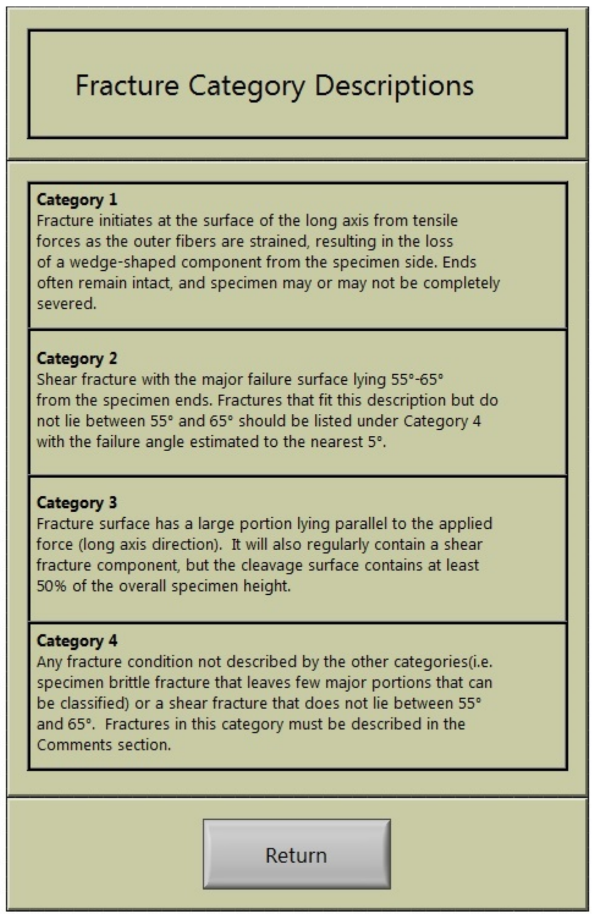


Figure 7. Fracture categorization results and description.

Young's Modulus and Shear Modulus

Sonic velocity tests were performed on 50 of the compression specimens before they were to calculate Young's and shear moduli. These tests were carried out via the appropriate ASTM standard[9] Charts of those data are shown in Figure 8 and Figure 9.

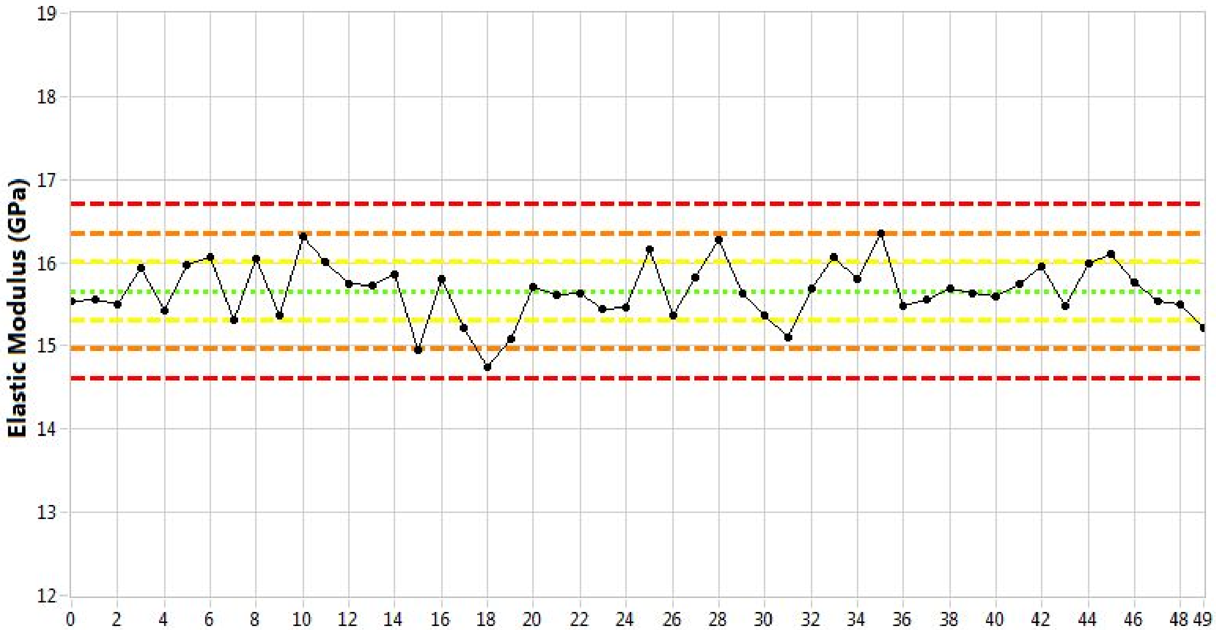


Figure 8. Elastic modulus by sonic velocity method (GPa), mean = 15.7, standard deviation = 0.3.

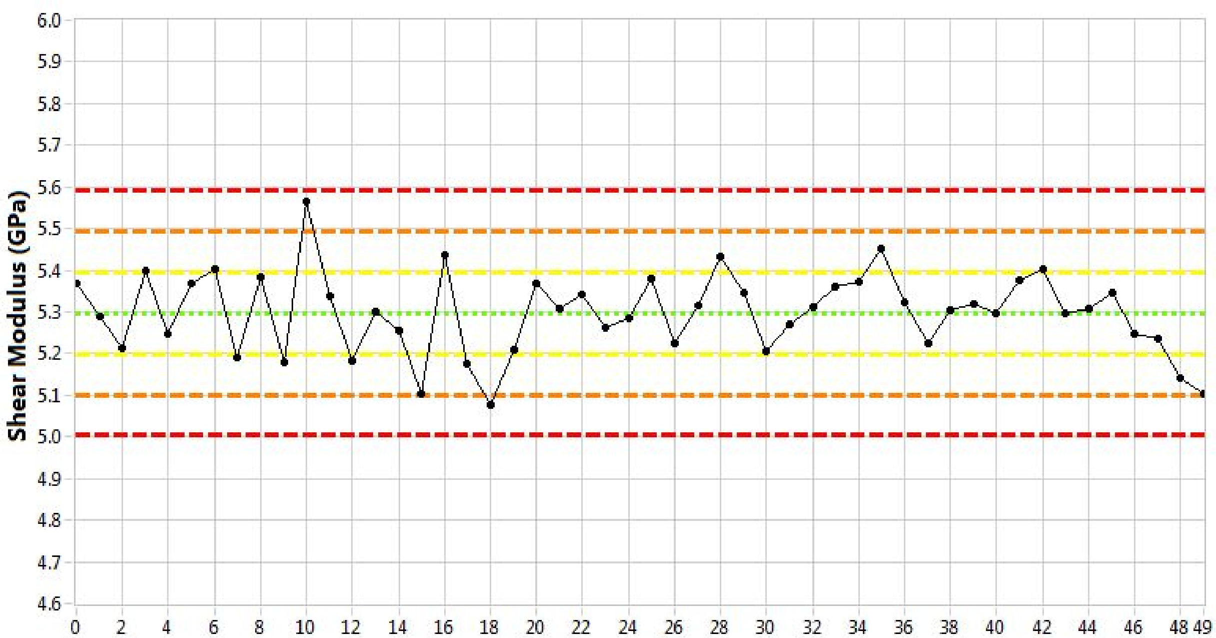


Figure 9. Shear modulus by sonic velocity method (GPa), mean = 5.3, standard deviation = 0.1.

Density Values

The relatively simple geometric shape of the compressive specimens provides an opportunity to collect density data (per ASTM C559-90[10]) for a large portion of the specimens extracted from each billet. While not a true performance property, density measurements are relatively straightforward to collect and are often reflective of bulk mechanical properties. The density values recorded for the compression specimens are shown in Figure 10. This plot shows a reasonable amount of material variation.

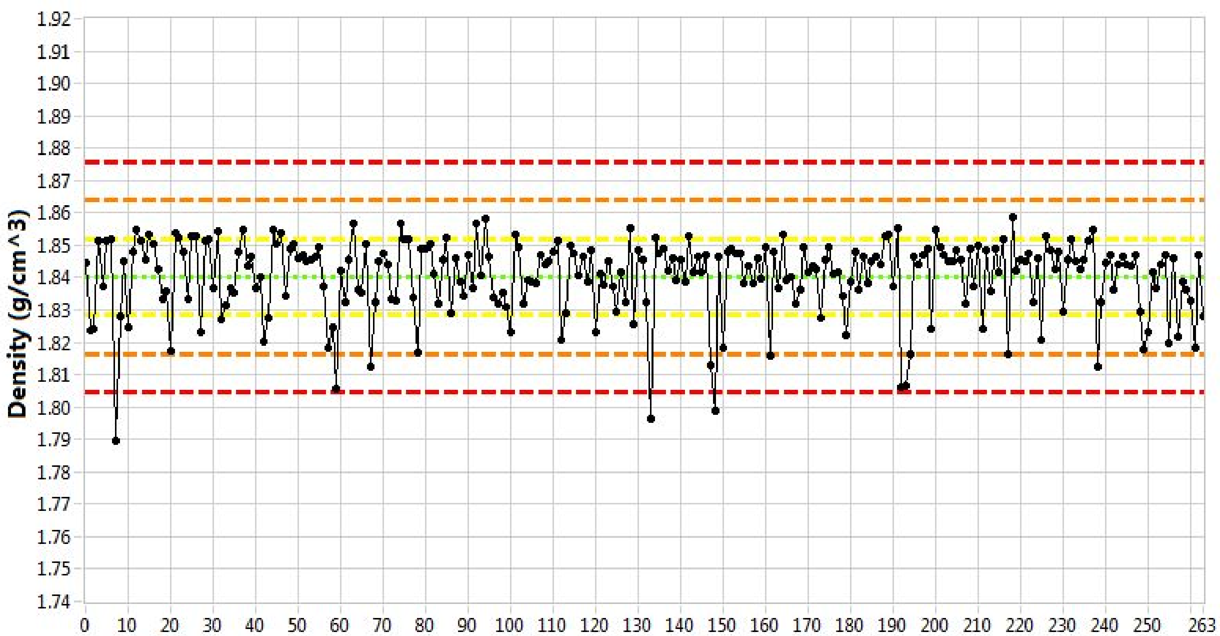


Figure 10. Density (g/cm^3), mean = 1.8402, standard deviation = 0.0118.

Flexural Specimen Database (NBG-18 635-4F)

Flexural Testing

Flexural testing was performed per ASTM C651-91,[11] with clarifications to ambiguities in the standard identified in PLN-3467.[3] Similar to the presentation of the compression specimen results, test validation lies not only in the documented adherence to applicable test plans and standards, but also in the noted correlations between recorded test properties and analyses for extreme or anomalous values. Additional verification of test conditions can be accomplished through an analysis of the physical characteristics of the specimens.

Figure 11 and Figure 12 show the relationship between flexural load and recorded flexural stress for the 260 specimens tested in flexure from NBG-18 635-4. Further comparisons and verification can be made with measured deflection (Figure 13), which will reflect an additional correlation with stress values through material elastic constants.

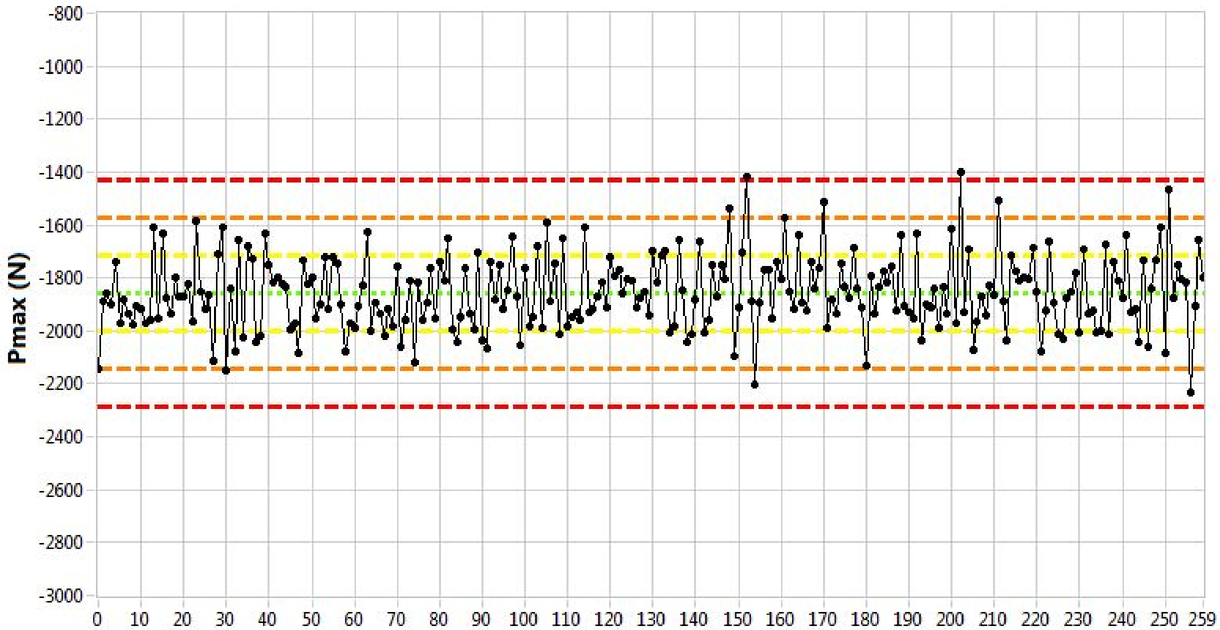


Figure 11. Max load (N), mean = -1856.6, standard deviation = 142.7.

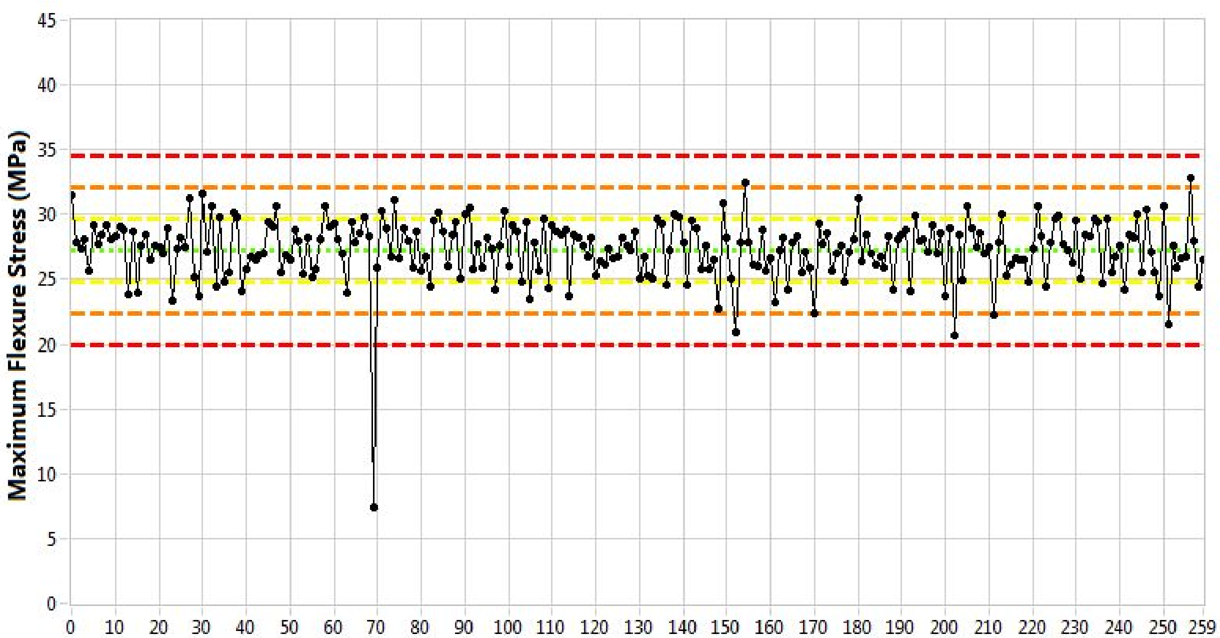


Figure 12. Maximum flexure stress (MPa), mean = 27.3, standard deviation = 2.4.

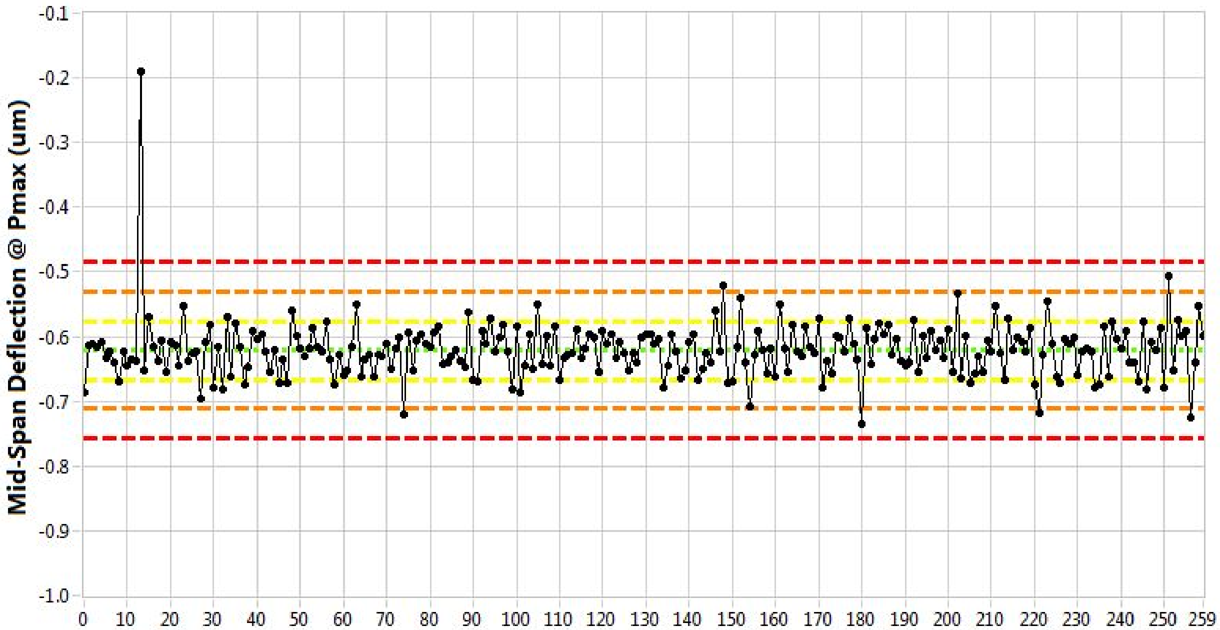


Figure 13. Mid-Span deflection at max load (um), mean = -0.6209, standard deviation = 0.0452.

Density Values

Similar to the compression specimens, the flexural specimens' geometry facilitated an opportunity to make density measurements.

Figure shows density from the flexural specimens. All flexural specimens' data and associated deviations compare well with the compression specimens' density data.

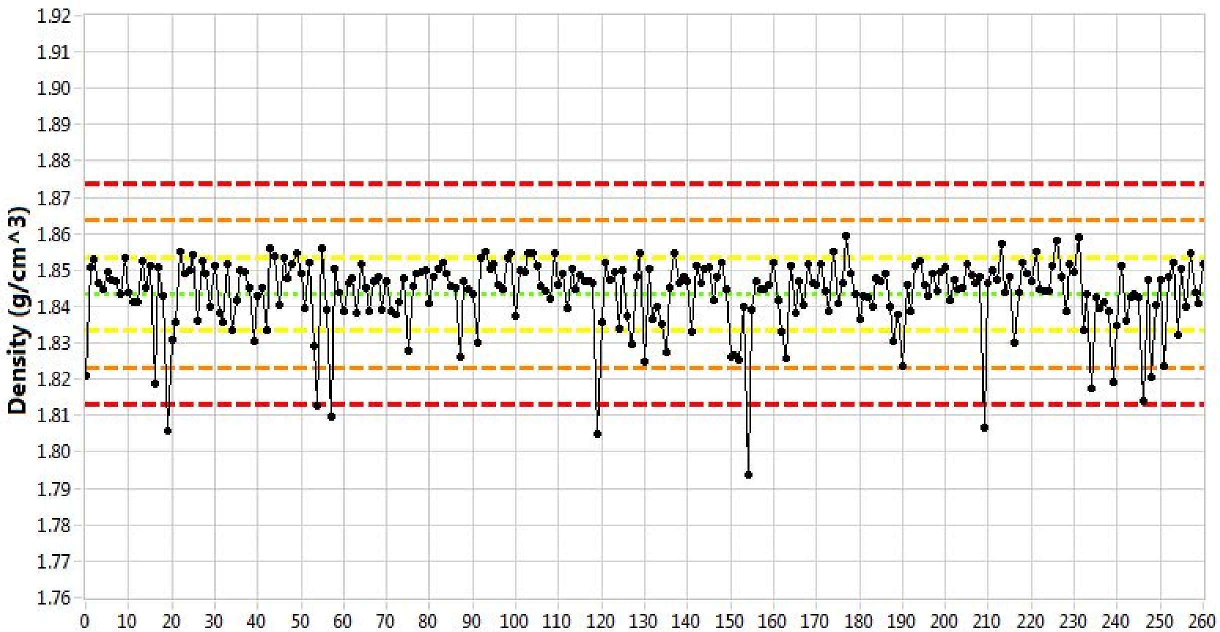


Figure 14. Density (g/cm3), mean = 1.8434, standard deviation = 0.0101.

Fundamental Frequency

The precise parallelepiped geometry of flexural specimens renders them particularly valuable for accurate measurements of fundamental frequency to calculate elastic constants for both dynamic Young's modulus and shear modulus (ASTM C747-93[12]). Values for fundamental frequency-based moduli, both in flexural and torsional modes, (shown in Figure 5 and Figure 6) are calculated from the equations provided in ASTM C1259-08.[13]

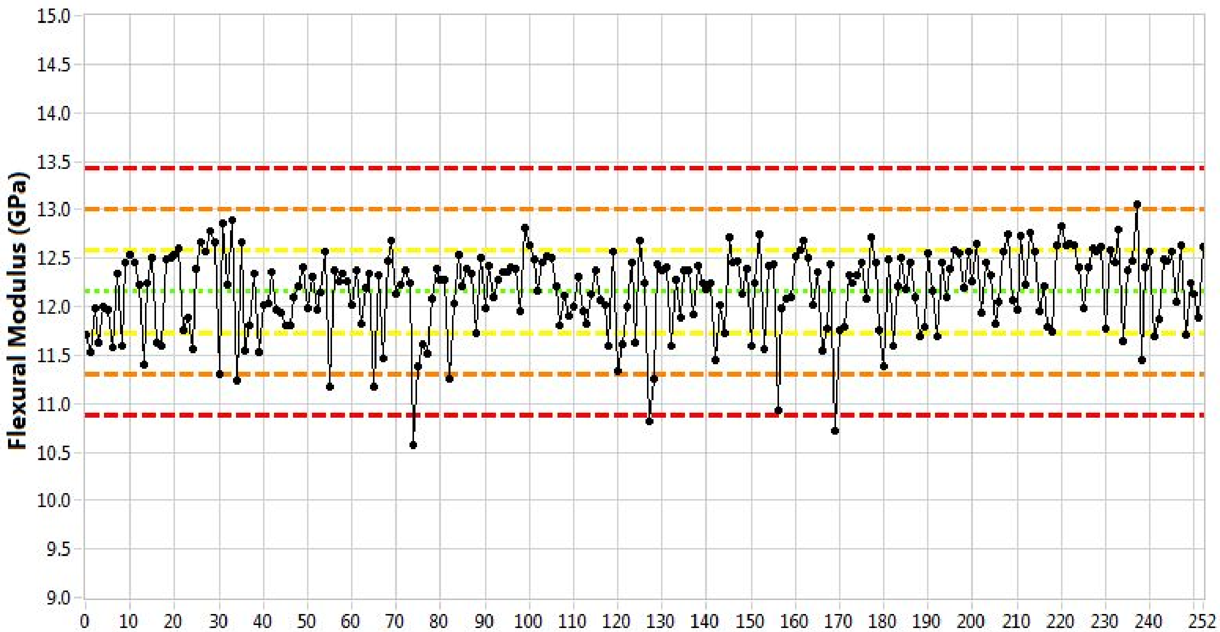


Figure 15. Flexural vibration mode modulus (GPa), mean = 12.2, standard deviation = 0.4.

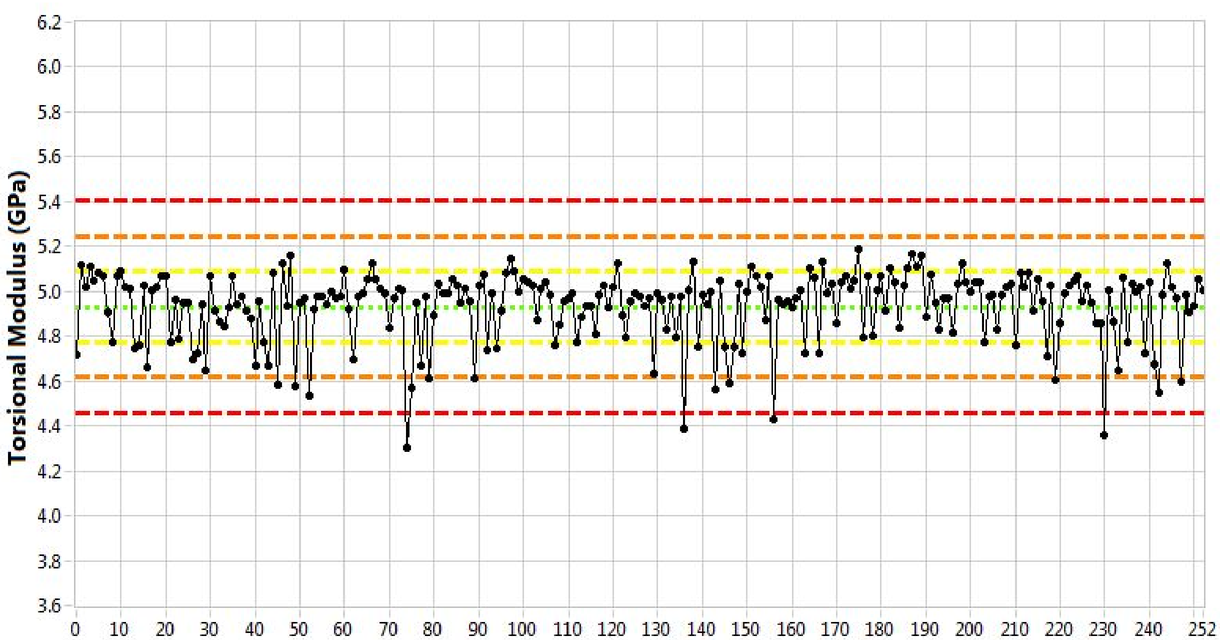


Figure 16. Torsional vibration mode shear modulus (GPa), mean = 4.9, standard deviation = 0.2.

Re-machined Specimen Properties

Two of the key components to direct comparisons between baseline and AGC data are (1) the analyses of specimens with similar geometries, and (2) the employment of similar test techniques for comprehensive validation. The large geometry of NBG-18 specimens provides the opportunity to "re-machine" unstressed specimen ends, as shown in Figure 7, to the same dimensions as AGC specimens in both creep and piggyback configurations. Using actual test specimens enables the continued employment of the specimen identification and tracking code system, as specimens are machined from tracked locations and can reuse the identification code.

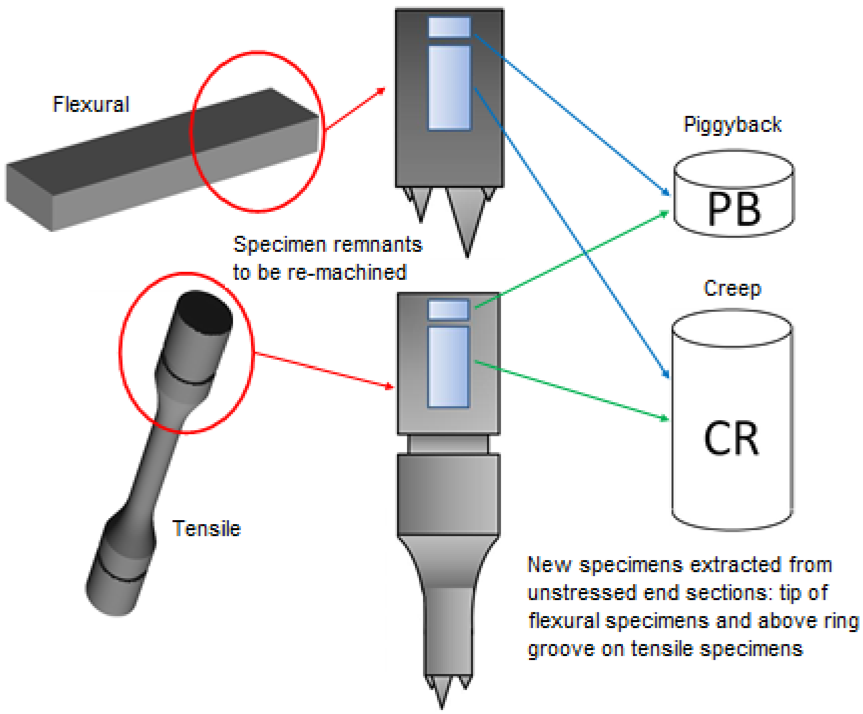


Figure 17. Unstressed remnants from tensile and flexural specimens are re-machined into AGC geometries.

The complete destruction of compression specimens does not allow the use of that particular specimen type, but a representative and random cross-section of flexural and tensile specimens were re-machined to repeat tests on AGC-based geometries (sonic velocity, fundamental frequency) or to perform tests that were otherwise not possible on mechanical test specimen geometries (coefficient of thermal expansion [CTE], diffusivity, and resistivity). Twenty-eight piggyback specimens and 30 creep specimens were machined from the remnants of the flexural specimens and 25 piggyback and 28 creep specimens were machined from the unstressed end of the tensile specimens. Similar data checks to the analyses outlined above were performed on each of these data sets, following the test procedures outlined for AGC-specific specimens described in detail in PLN-3267.[4]

Re-Machined Sonic Velocity

As with Figure 8 and Figure 9, sonic velocity measurements provide a means to calculate elastic constant values for re-machined specimens (Figure and Figure).

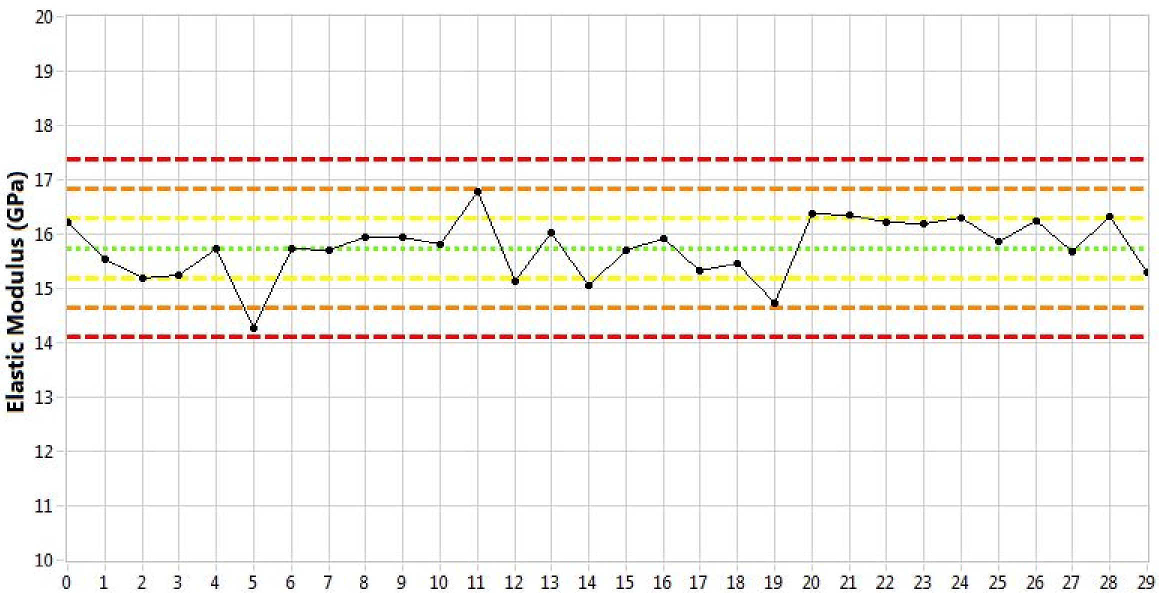


Figure 18. Re-machined flexural specimen (creep specimens), Young's modulus by sonic velocity (GPa), mean = 15.7, standard deviation = 0.5.

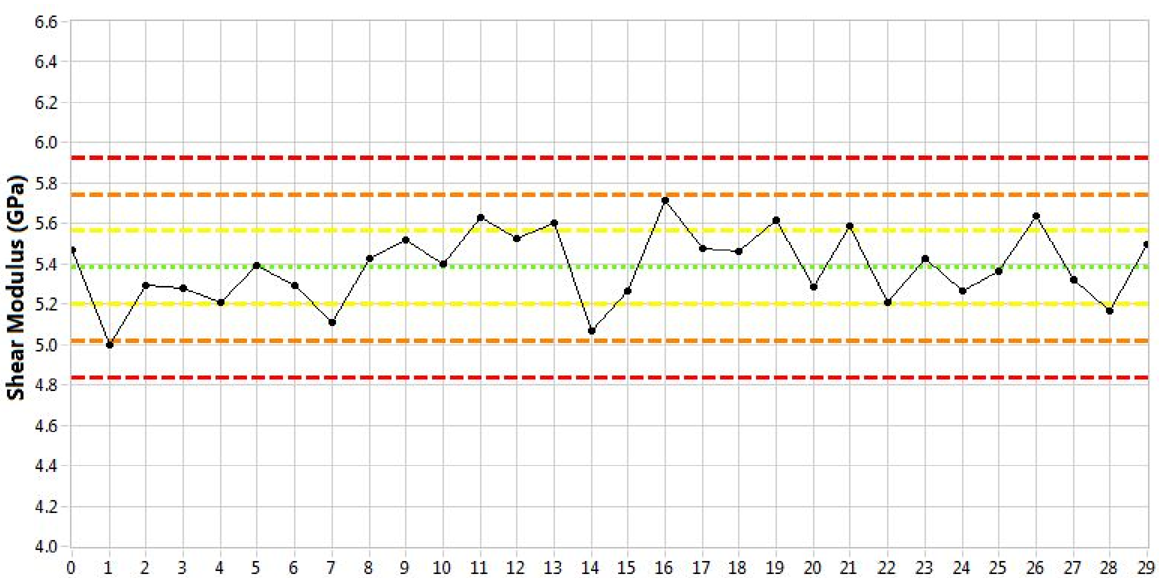


Figure 19. Re-machined flexural specimen (creep specimens), shear modulus by sonic velocity (GPa), mean = 5.4, standard deviation = 0.2.

Re-machined Fundamental Frequency

Values reflected in the elastic constants gained through ringing creep specimens (Figure) are comparable with the values obtained using specimens with ideally shaped long parallelepiped specimens (see Figure 16 above). Test verification is bolstered through a comparison of frequency values with calculated modulus values, which should track very closely with slight offsets resulting from machined dimensional variations.

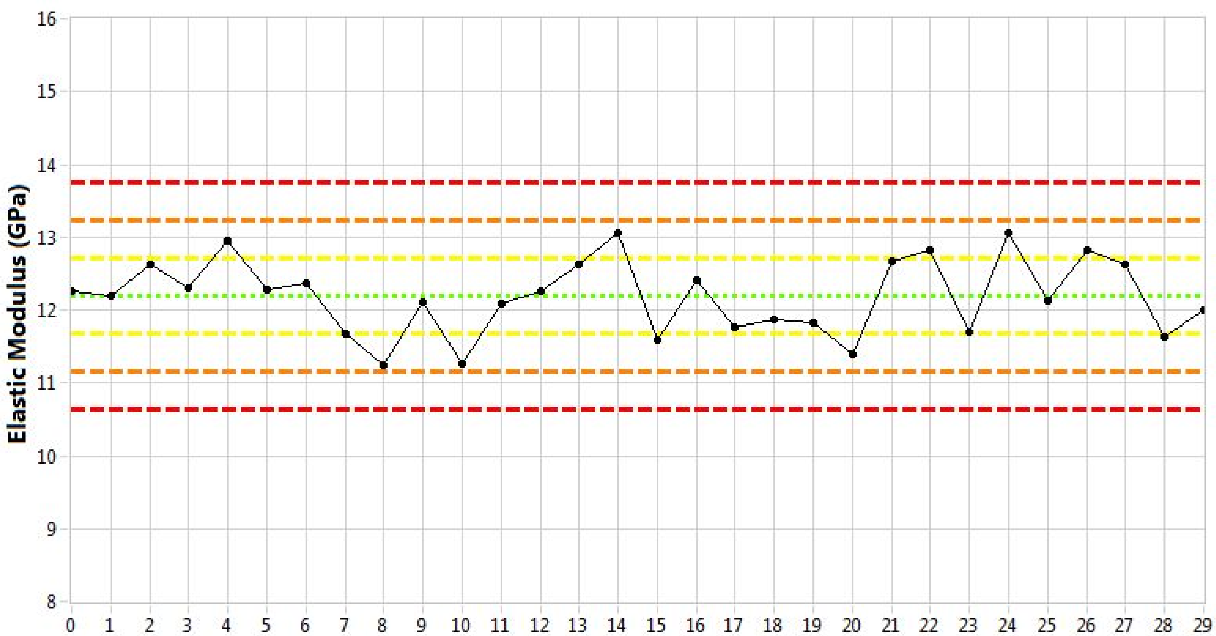


Figure 20. Re-machined flexural specimen (creep specimens), Young's modulus by sonic resonance (GPa), mean = 12.2, standard deviation = 0.5.

Re-machined Specimen Resistivity

Electrical resistivity values shown in Figure are recorded per ASTM C611-05.[14] Recording of resistivity provides a relatively simple method for determining internal flaws in a specific specimen. Deviations from the recommended specimen size, which are otherwise impractical for AGC testing, are identified in PLN-3267.[4]

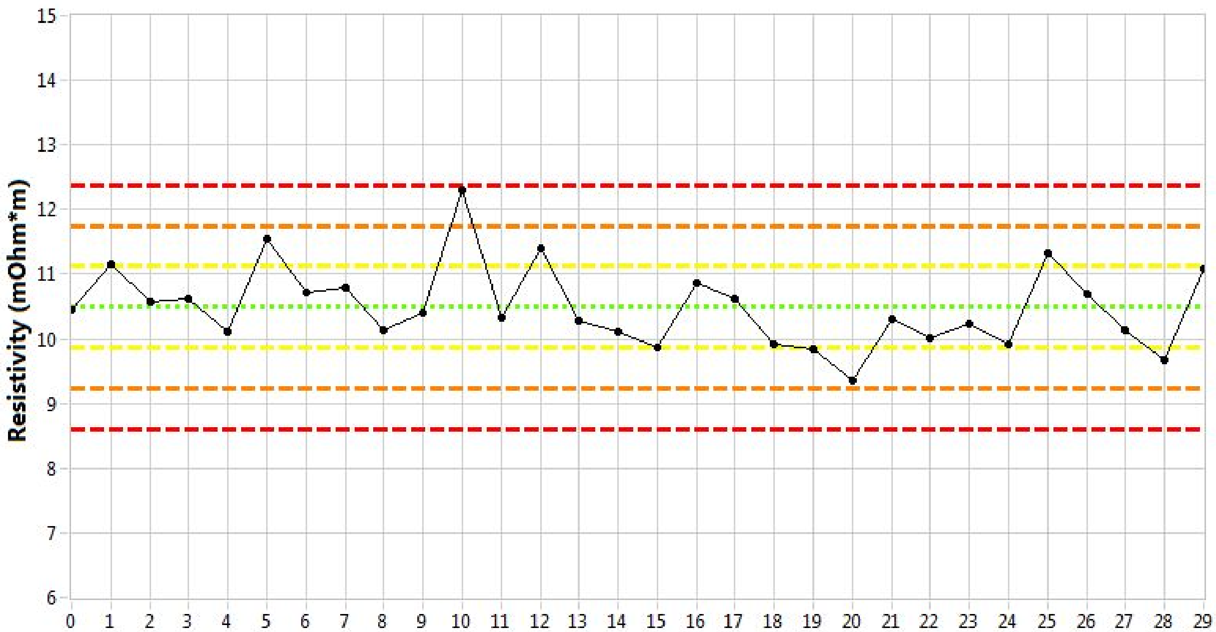


Figure 21. Re-machined flexural specimen (creep specimens), resistivity (μΩ-m), mean = 10.5, standard deviation = 0.6.

Re-Machined Specimen Diffusivity

Thermal diffusivity values are collected from the piggyback specimens per ASTM E1461-07.[15] The diffusion of heat through the specimen following the application of thermal energy via a laser source demonstrates the heat transfer characteristics, and can be used to calculate thermal conductivity for design purposes. The resulting group of diffusivity values, revealing a tight grouping of thermal transfer characteristics, is shown in Figure .

Re-Machined Specimen Coefficient of Thermal Expansion

An additional evaluation for the thermal response characteristics of graphite, which are extremely important for energy conversion systems, is the coefficient of thermal expansion (CTE). CTE is measured by carefully tracking the change in the specimen's length while changing temperature ranges, as described in ASTM E228-06.[16] The mean CTE results are shown in Figure .

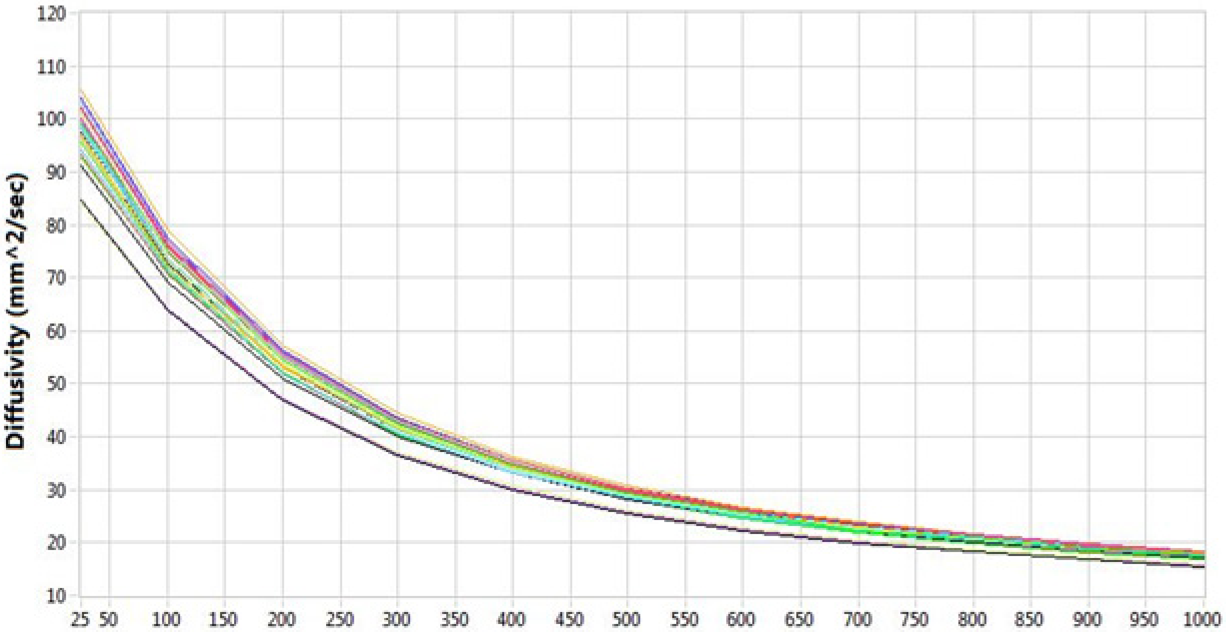


Figure 22. Re-machined flexural specimen (piggyback specimens), diffusivity (mm^2/sec).

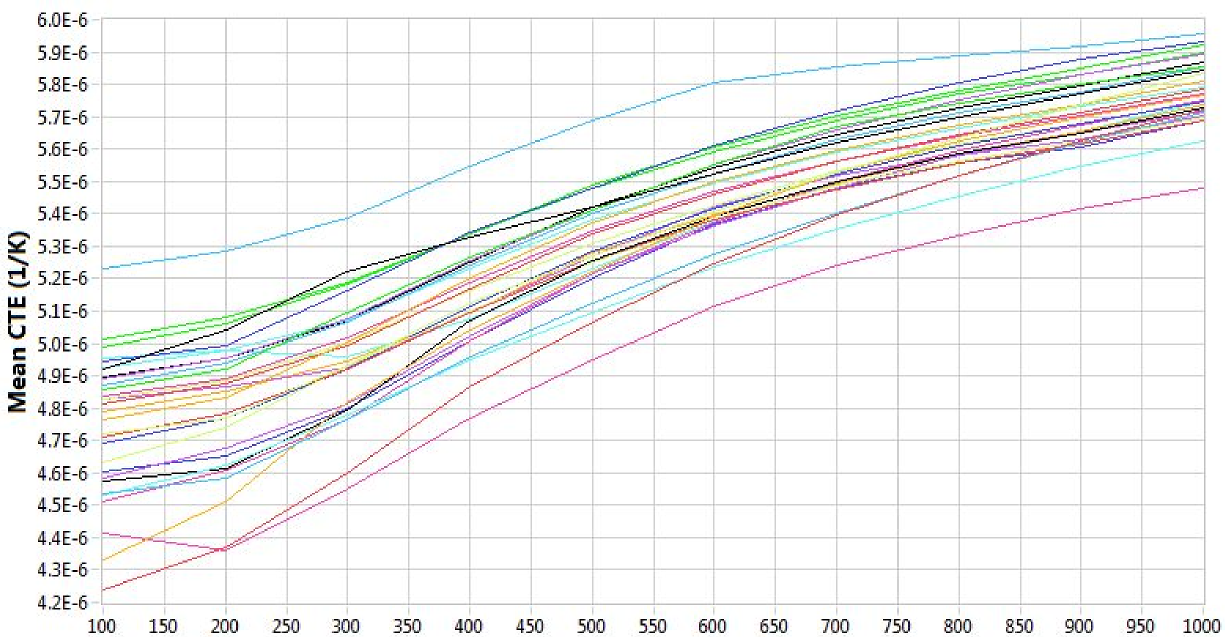


Figure 23. Re-machined flexural specimen (creep specimens), CTE (1/K).

Tensile Specimen Database (NBG-18 635-4T)

Tensile Testing

Tensile testing was performed per ASTM C749-08.[17] Data verification follows the principles discussed in previous sections. As with other specimen types, data verification lies not only in documented adherence to applicable test plans and standards, but in noted correlations between recorded test properties and analyses of outlying values. Additional verification of test conditions can be carried out through an analysis of ancillary physical characteristics. The custom measurement software used to capture tensile specimen gauge diameters is programmed to flag any measurement that deviates from the ASTM standard. With exception of one specimen, all of the gauge diameter measurements fell within +/- 3 standard deviations of the mean. However, two of the gauge diameter measurements were flagged by the software as not meeting the ASTM requirements (gauge diameters measurements must fall within the interval 15.88 +/- 0.05 mm) (see Figure 24). Because of this, they were removed from further testing.

Four of the specimens experienced errors during the tensile testing. Therefore, these four specimens' data are not included in the final data set. Figure 25 and Figure 26 show the relationship between tensile load and recorded tensile stress for the remaining 253 specimens tested in uniaxial tension from the NBG-18 635-4 billet. Further comparisons and verification can be made with extensometer-based measured deflection (shown in Figure 27), which will reflect an additional correlation with stress values through material elastic constants. Comparing the extreme values again shows this relationship to be valid.

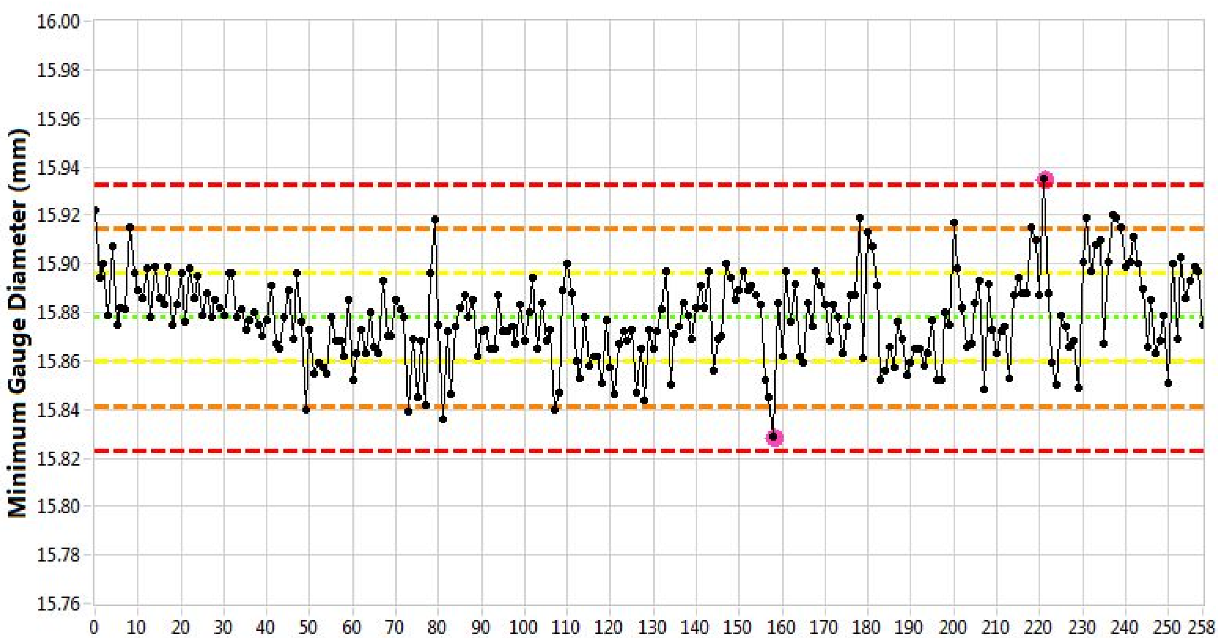


Figure 24. Minimum gauge diameter (mm), mean = 15.878, standard deviation = 0.018. The highlighted points represent the two specimens which did not meet ASTM dimensional requirements.

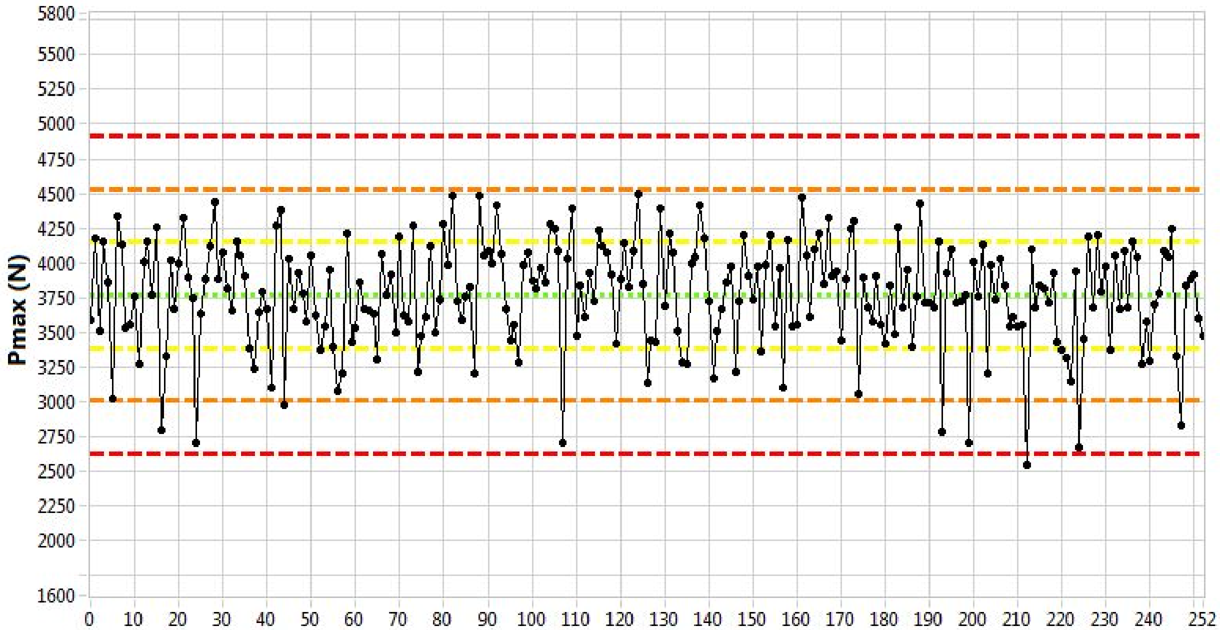


Figure 25. Maximum load (N), mean = 3767, standard deviation = 382.

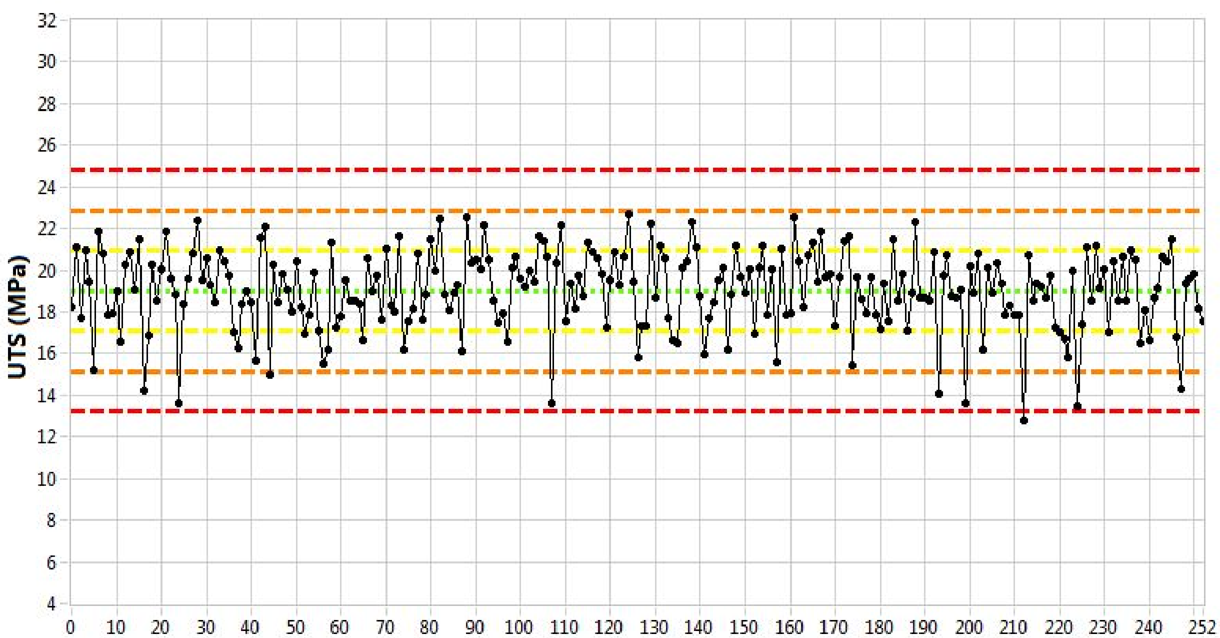


Figure 26. Ultimate tensile strength (MPa), mean = 19.0, standard deviation = 1.9.

Title: Baseline Characterization Database Verification Report – NBG-18 Billet 635-4

ECAR No.: 3677 Rev. No.: 0 Project No.: 32138 Date: 07/12/2017

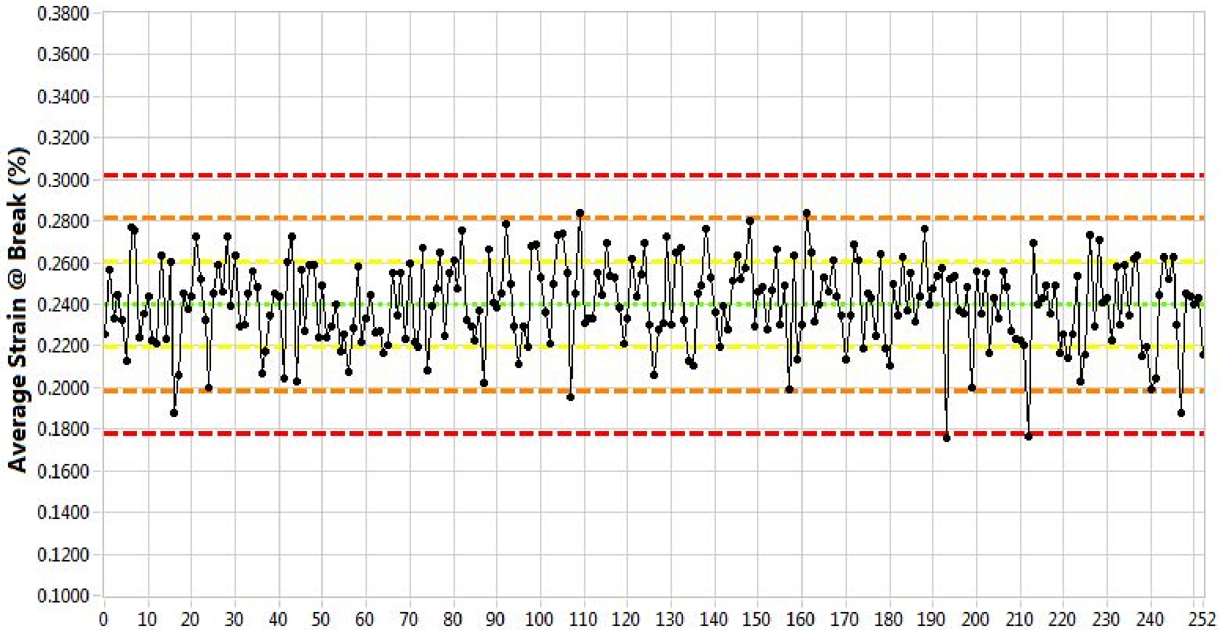


Figure 27. Average strain at break (%), mean = 0.24, standard deviation = 0.02.

Re-Machined Sonic Velocity

Similar to the manner in which the data was reported for re-machined flexural specimens, sonic velocity-based modulus values for specimens extracted from broken tensile test bars are given in Figure 28 and Figure 29.

Re-Machined Resonant Frequency Testing

Resonant frequency values for the re-machined tensile specimens are given in Figure 30. The modulus values track well with recorded frequency values, and averaging roughly 12 GPa, correlate well with measured resonant frequency-based modulus values from other specimens (Figure and Figure).

Re-Machined Resistivity Values

The recorded resistivity values for the re-machined tensile specimens in the creep geometry are shown in Figure 31. As has been discussed earlier, some variation does exist, but as resistivity calculations rely on a number of measured parameters, the lack of any severely deviating points is evidence of the validity of each of the points.

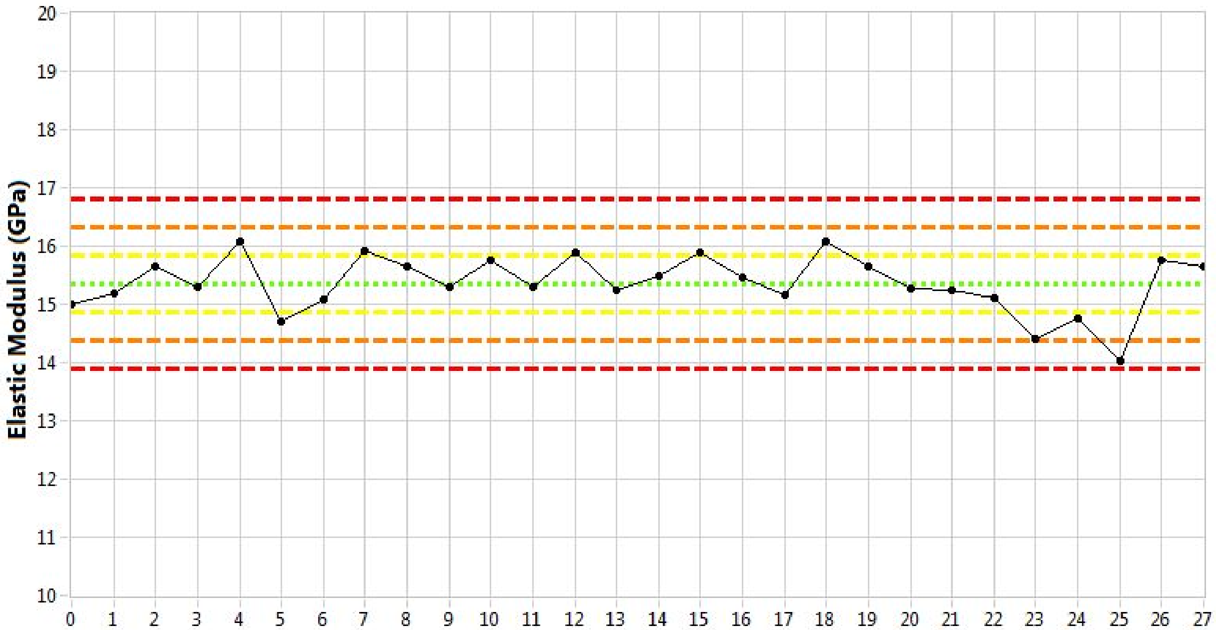


Figure 28. Re-machined tensile specimen (creep specimens), Young's modulus by sonic velocity (GPa), mean = 15.4, standard deviation = 0.49.

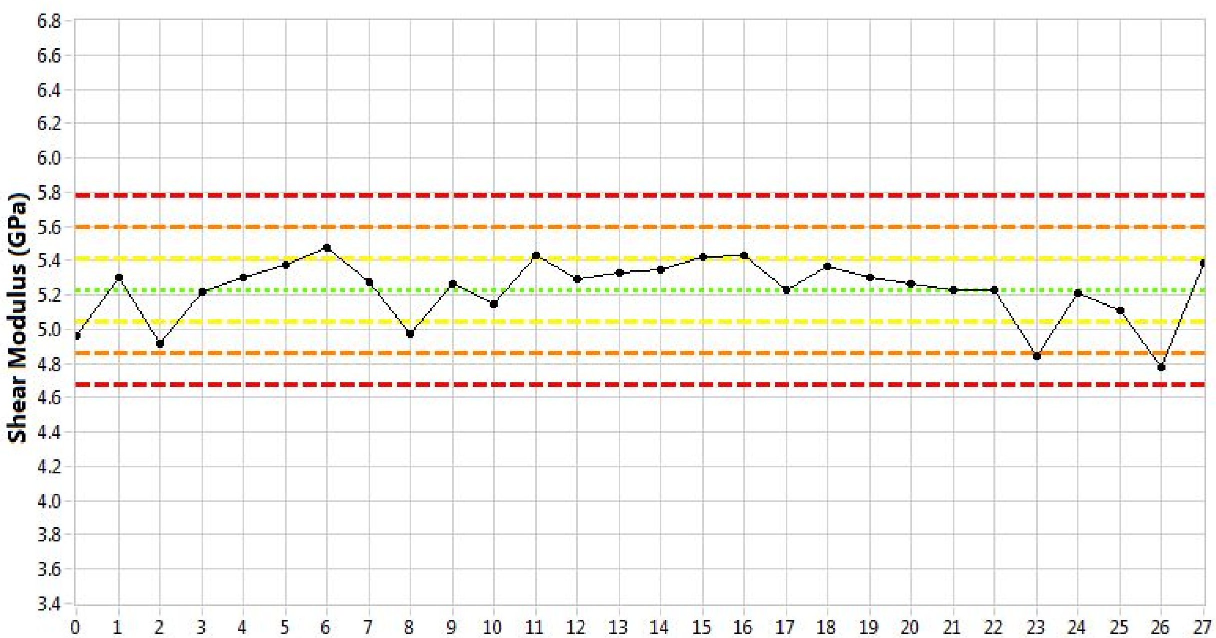


Figure 29. Re-machined tensile specimen (creep specimens), shear modulus by sonic velocity (GPa), mean = 5.2, standard deviation = 0.18.

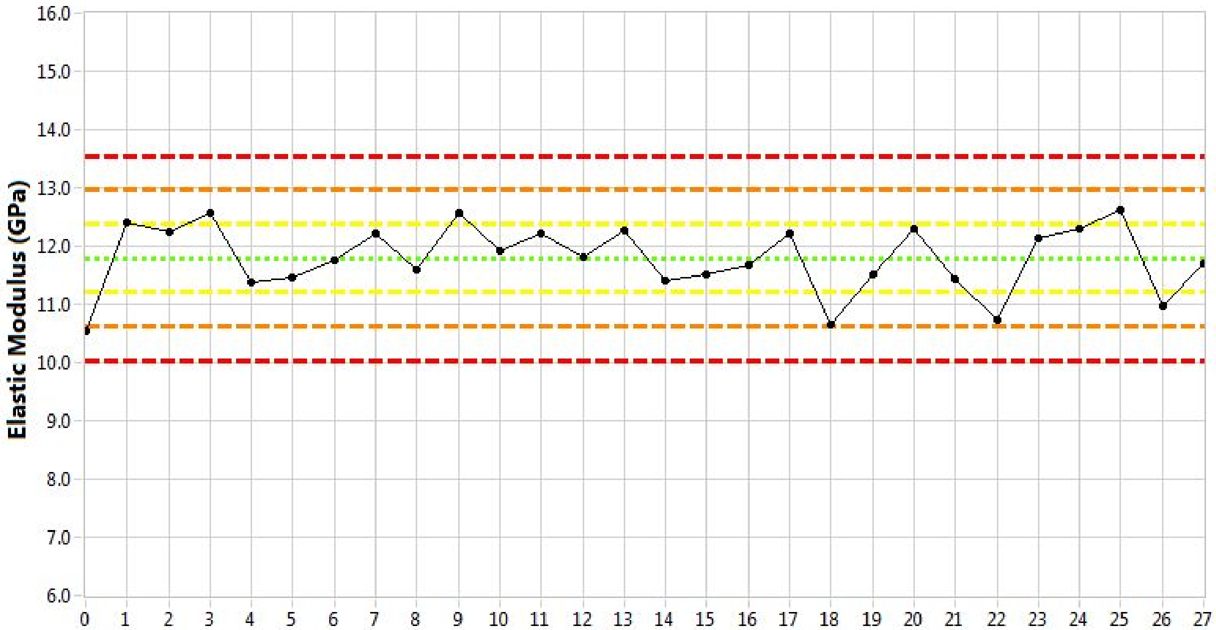


Figure 30. Re-machined tensile specimen (creep specimens), Young's modulus by sonic resonance method (GPa), mean = 11.8, standard deviation = 0.59.

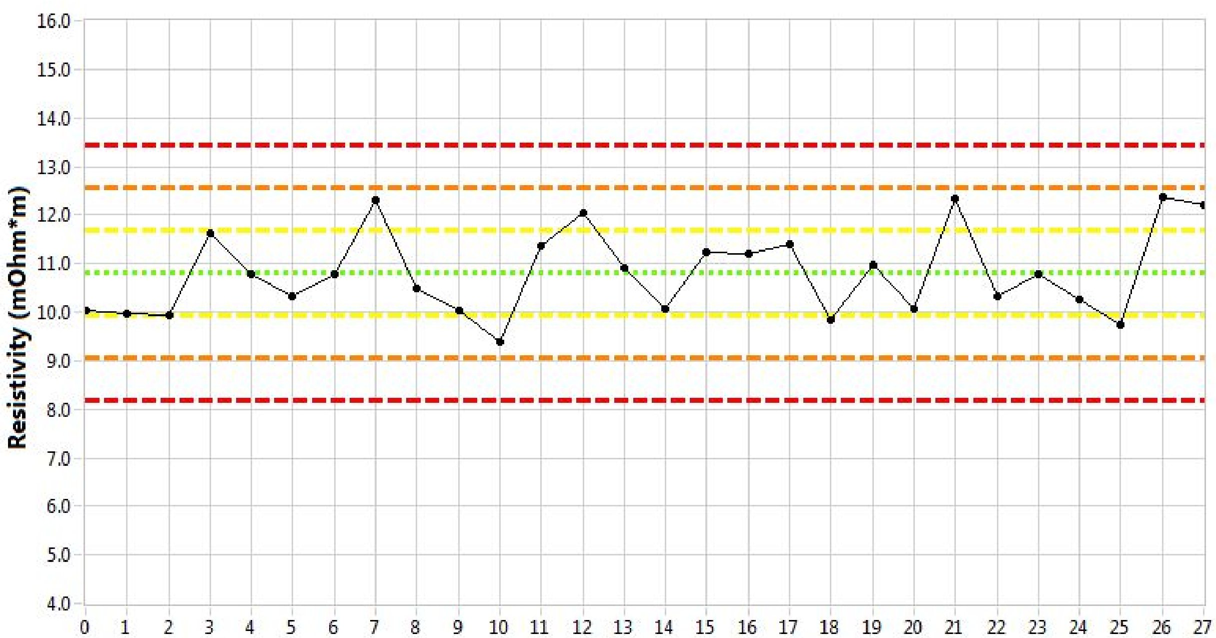


Figure 31. Re-machined tensile specimen (creep specimens), resistivity ($\mu\Omega$-m), mean = 10.8, standard deviation = 0.88.

RE-MACHINED SPLIT DISC TESTING

Disc splitting tensile strength testing was performed in accordance with PLN-3348, Revision 4, Section 6.1.1.5. This allows for a direct comparison of tensile strength data to data that were acquired through strict application of ASTM C749-08 (Figure 26). Figure 32 and Figure 33 show strength and load data from the disc splitting testing.

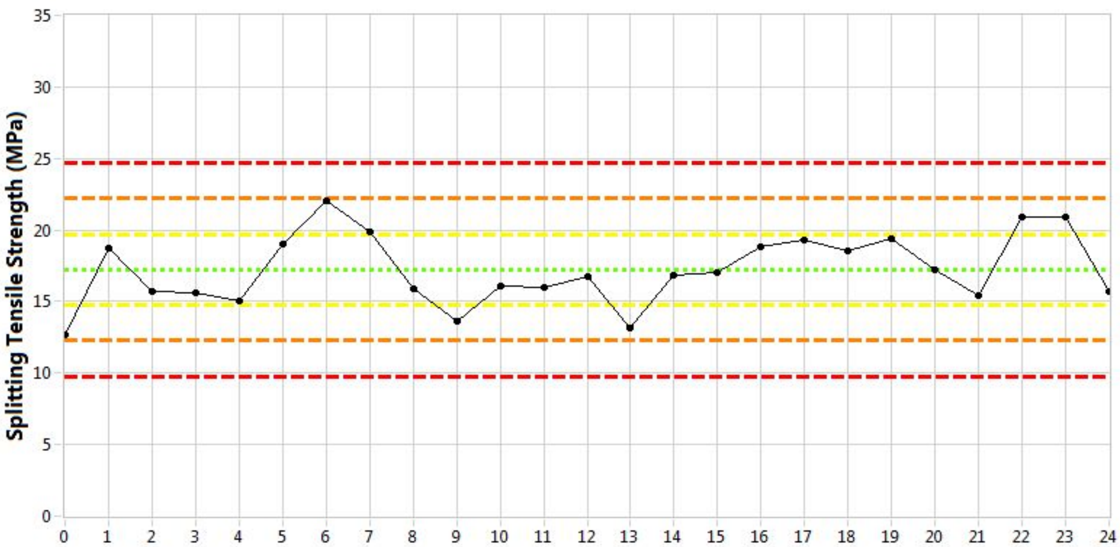


Figure 32. Disc splitting tensile strength (MPa), mean = 17.2, standard deviation = 2.5.

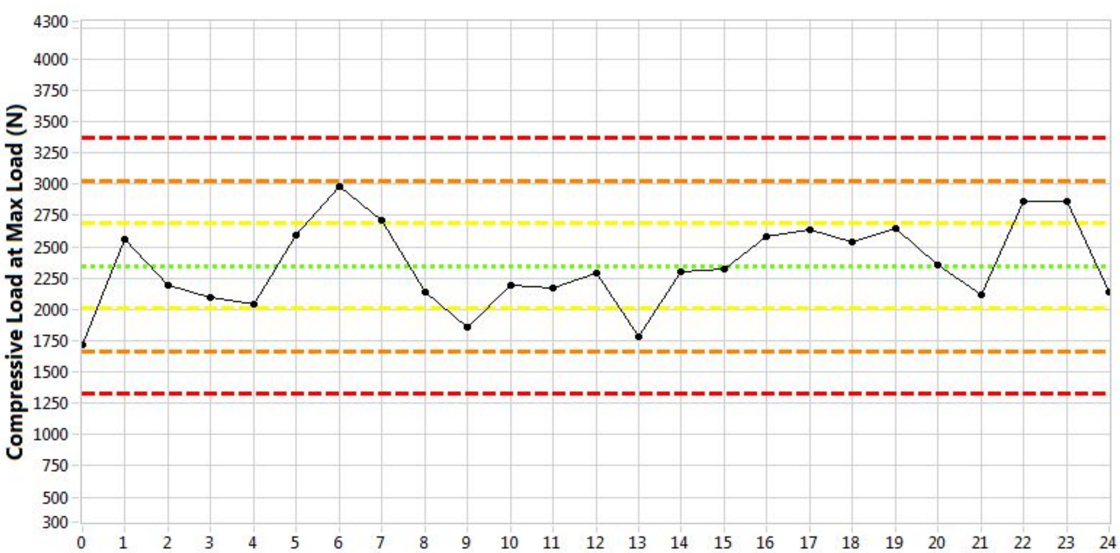


Figure 33. Disc splitting compressive load at max load (N), mean = 2,347, standard deviation = 339.6.

RE-MACHINED SPECIMEN DIFFUSIVITY

Thermal diffusivity values are collected from the re-machined tensile specimens per ASTM E1461-07.[15] Diffusion of heat through the specimen following application of thermal energy via a laser source demonstrates heat transfer characteristics and can be used to calculate thermal conductivity for design purposes. The resulting group of diffusivity values, revealing a tight grouping of thermal transfer characteristics, is shown in Figure 34.

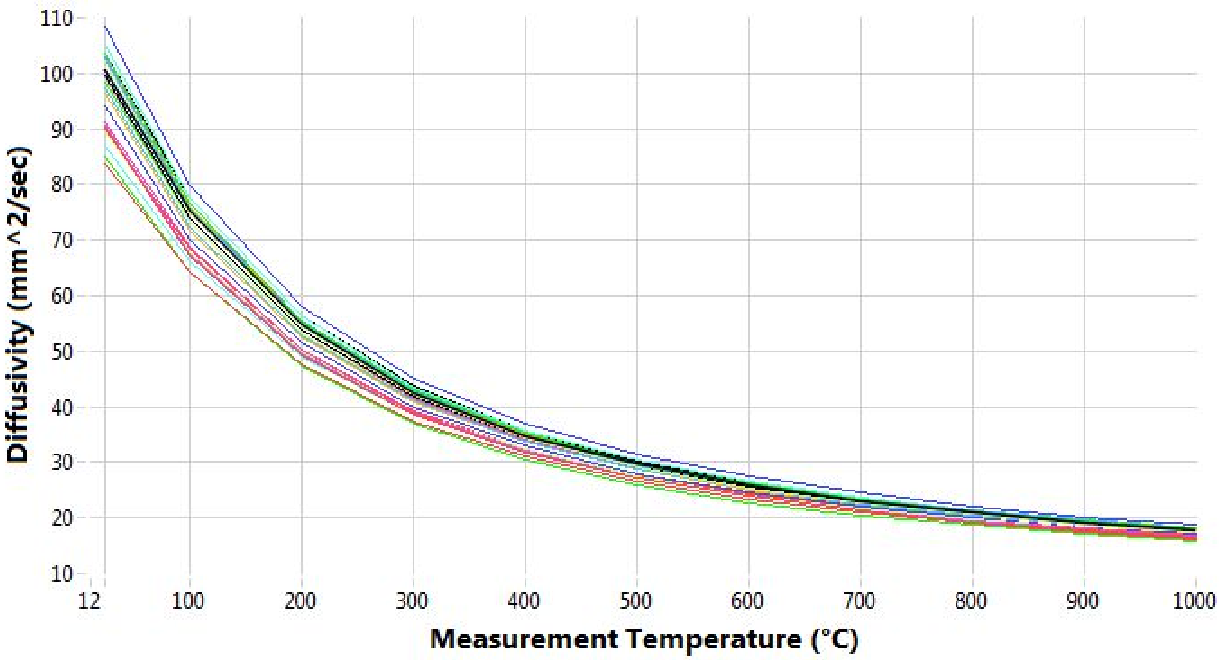


Figure 34. Re-machined specimen diffusivity.

SUMMARY

Comprehensive data sets for the NBG-18 Billet 635-4 have been compiled into summary files of property scalar values. The data spreadsheet files are divided by mechanical test specimen type into three main sets: (1) compressive, (2) flexural, and (3) tensile. The multitude of tests and evaluations performed on each specimen type are individually tabbed in the main data set files.

In addition to a full visual review of the data files to determine if obvious errors were made with the data collected (e.g., missing information or otherwise blank cells), graphical representations were made of individual evaluations to provide a means to spot anomalies. A review of the data indicates that the files, as submitted, are fully representative of the measured properties of the graphite billets being tested, as outlined in the applicable test procedures and program plans.

REFERENCES

1. PLN-2497, 2010, "Graphite Technology Development Plan," Revision 1, October 2010.

2. PLN-3348, 2011, "Graphite Mechanical Testing," Revision 2, April 2011.

3. PLN-3467, 2011, "Baseline Graphite Characterization Plan: Electromechanical Testing," Revision 1, August 2011.

4. PLN-3267, 2010, "AGC-2 Characterization Plan," Revision 0, March 2010.

5. Carroll, Mark, Joe Lord, and David Rohrbaugh, 2010, *Baseline Graphite Characterization: First Billet*, INL/EXT-10-19910, September 2010.

6. LAB 2143, "Baseline Graphite Characterization," December 2013.

7. LWP-20000-01, "Conduct of Research Plan," Revision 0, December 2015.

8. ASTM Standard C695-15, 2015, "Standard Test Method for Compressive Strength of Carbon and Graphite," ASTM International.

9. ASTM Standard C769-09, 2009, "Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Material for Use in Obtaining an Approximate Young's Modulus," ASTM International.

10. ASTM Standard C559-90, reapproved 2005, "Standard Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles," ASTM International.

11. ASTM Standard C651-91, reapproved 2005, "Standard Test Method for Flexural Strength of Manufactured Carbon and Graphite Articles Using Four-Point Loading at Room Temperature," ASTM International, 2005.

12. ASTM Standard C747-93 (Reapproved 2005), "Standard Test Method for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance," ASTM International.

13. ASTM Standard C1259-08, 2008, "Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration," ASTM International.

14. ASTM Standard C611-05, 2005, "Standard Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature," ASTM International.

15. ASTM Standard E1461-07, 2007, "Standard Test Method for Thermal Diffusivity by the Flash Method," ASTM International.

16. ASTM Standard E228-06, 2006, "Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push Rod Dilatometer," ASTM International.

17. ASTM Standard C749-08, 2008, "Standard Test Method for Tensile Stress-Strain of Carbon and Graphite," ASTM International.

Appendix A

Additional Compression Specimen Database Plots (NBG-18 635-4C)

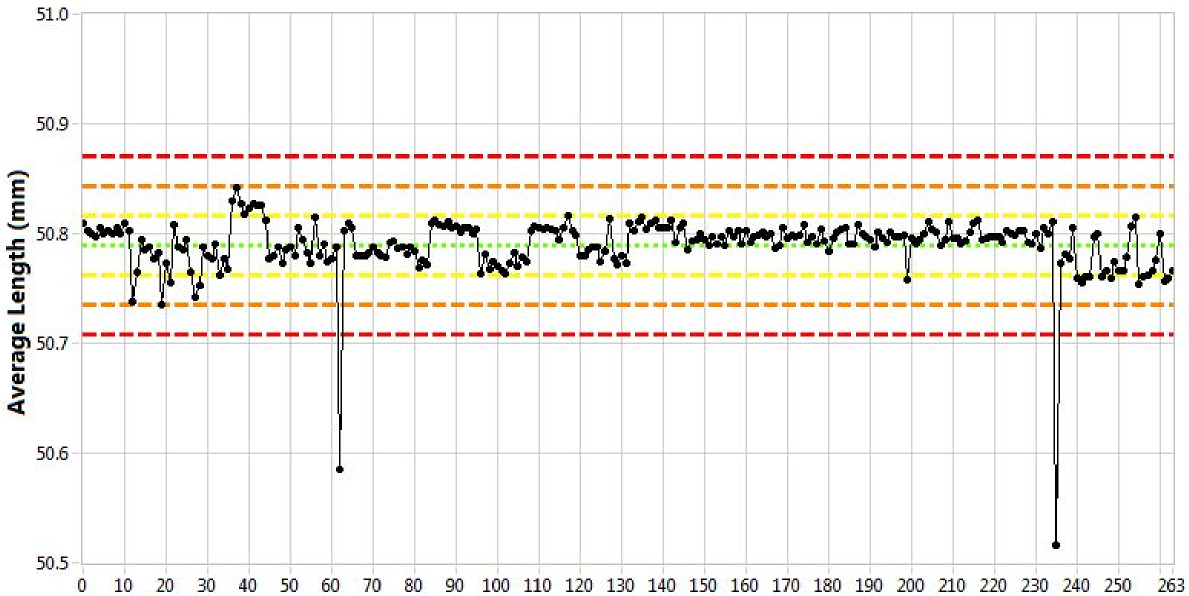


Figure A-1. Average length (mm), mean = 50.79, standard deviation = 0.027.

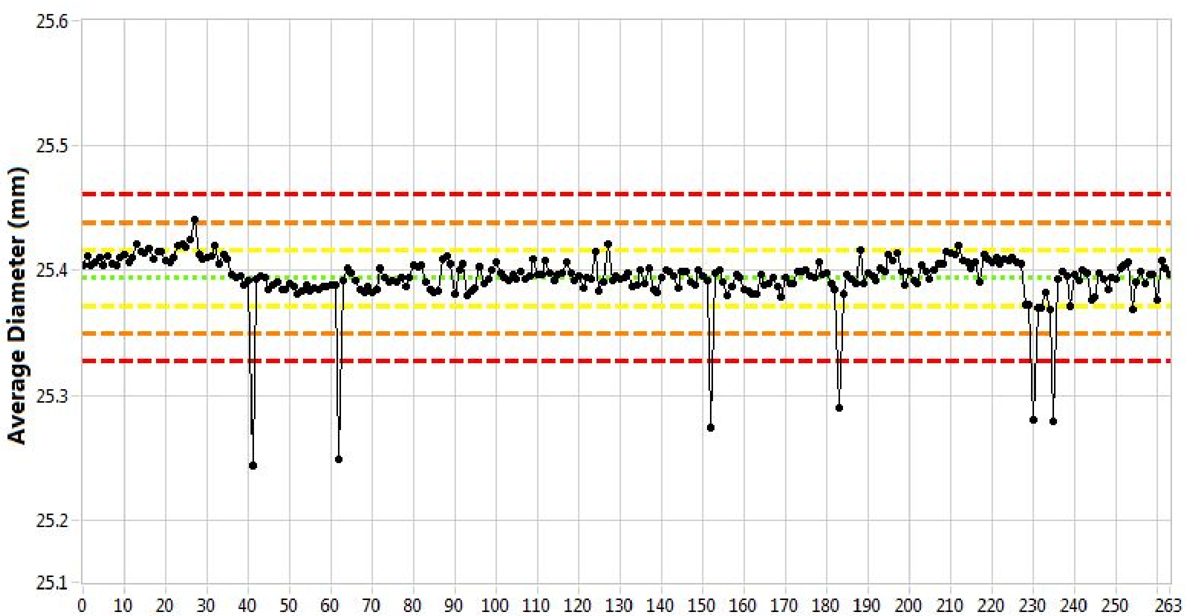


Figure A-2. Average diameter (mm), mean = 25.394, standard deviation = 0.022.

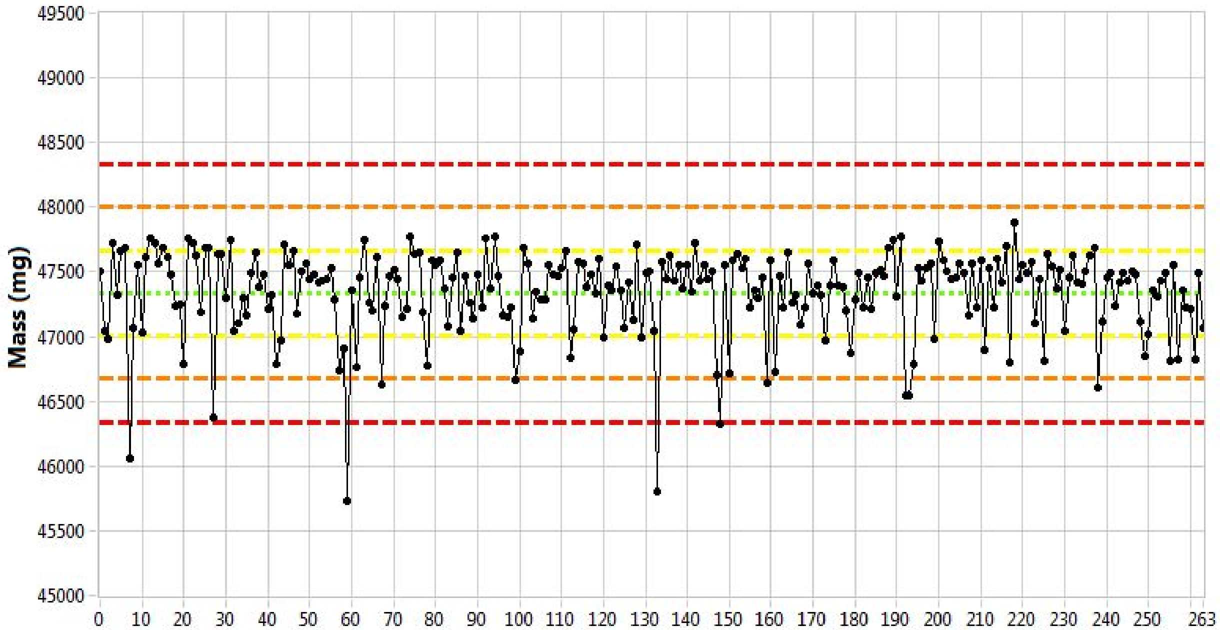


Figure A-3. Mass (mg), mean = 47,338, standard deviation = 332.

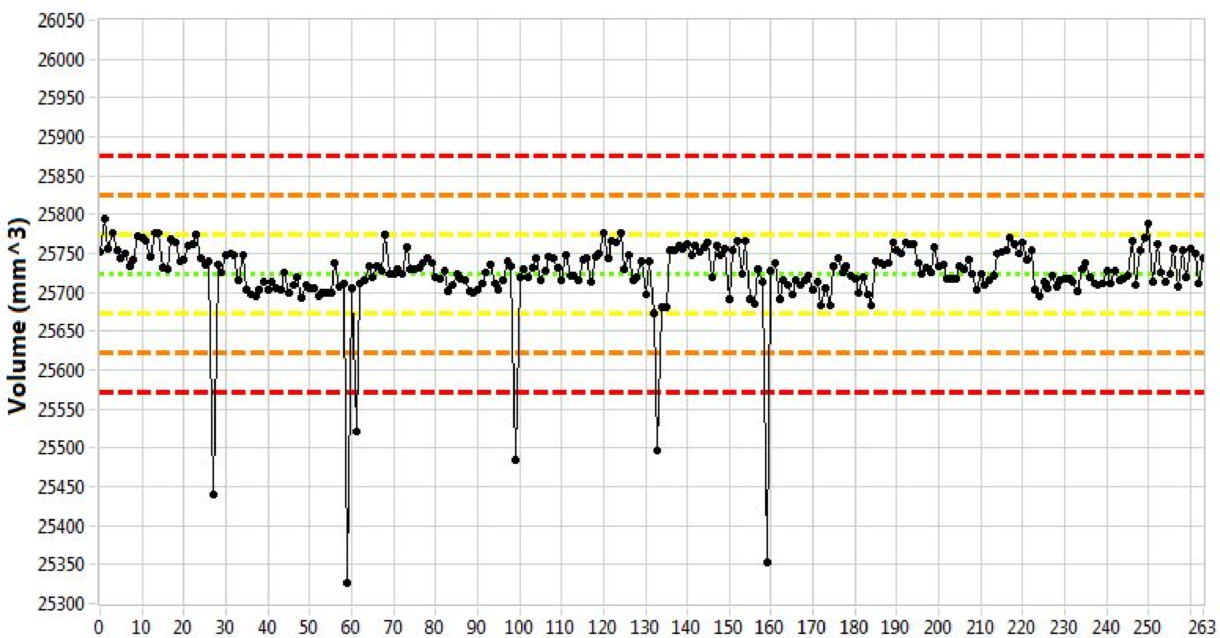


Figure A-4. Volume (mm^3), mean = 25,724, standard deviation = 51.

Appendix B

Additional Flexural Specimen Database Plots (NBG-18 635-4F)

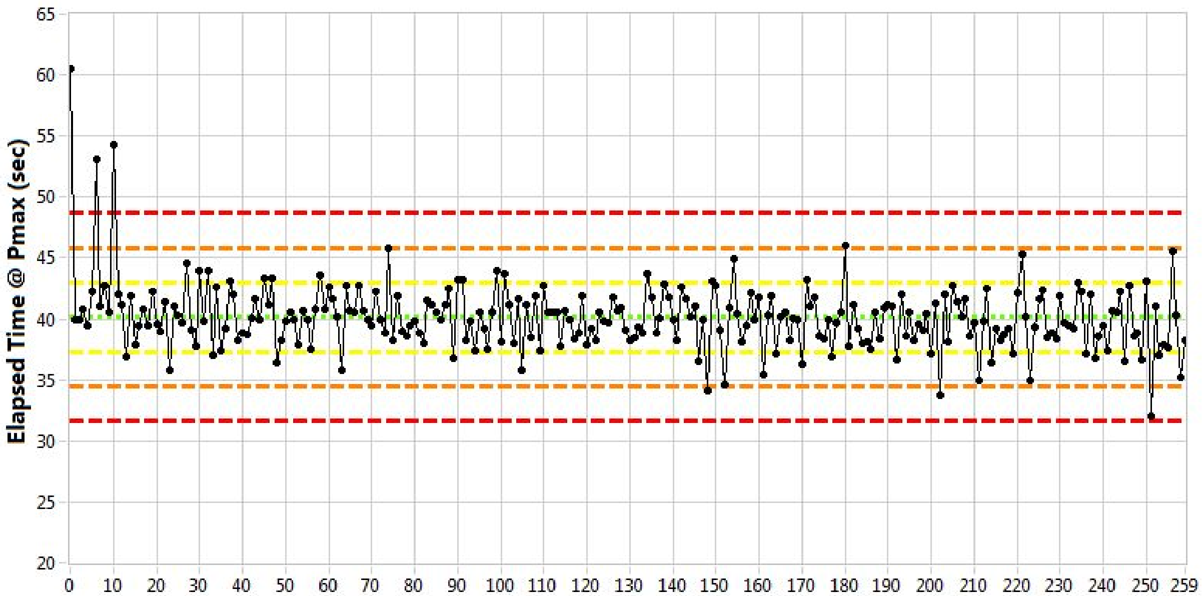


Figure B-1. Elapsed time at maximum load (sec), mean = 40.1, standard deviation = 2.8.

Figure B-2. Average width (mm), mean = 31.758, standard deviation = 0.015.

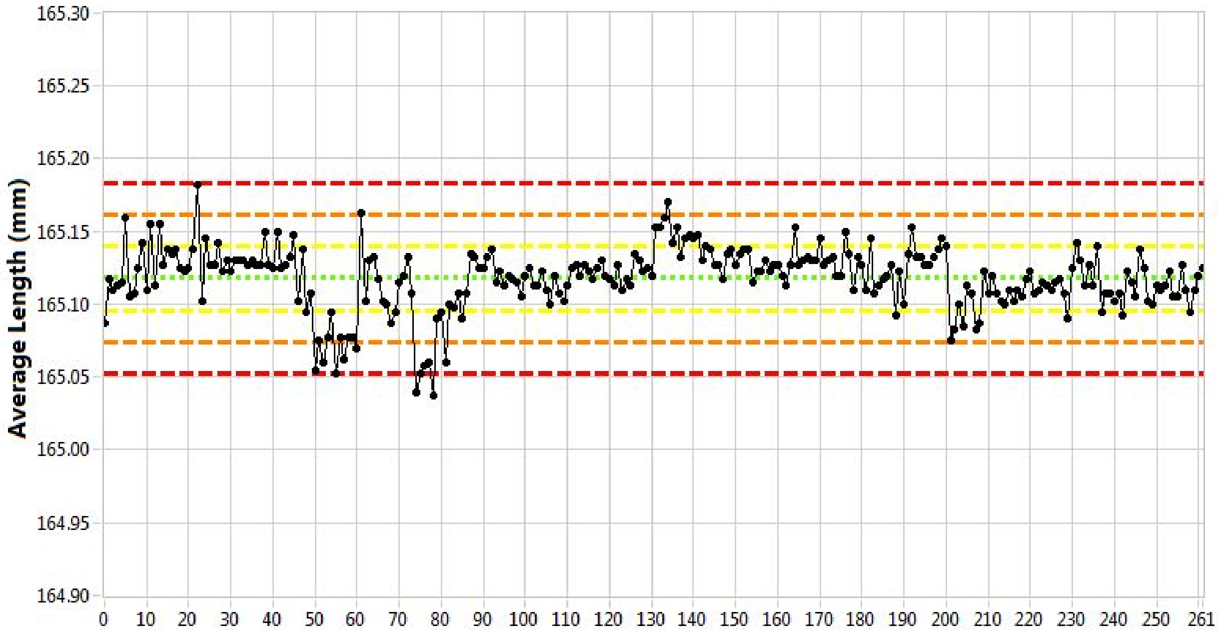


Figure B-3. Average length (mm), mean = 165.118, standard deviation = 0.022.

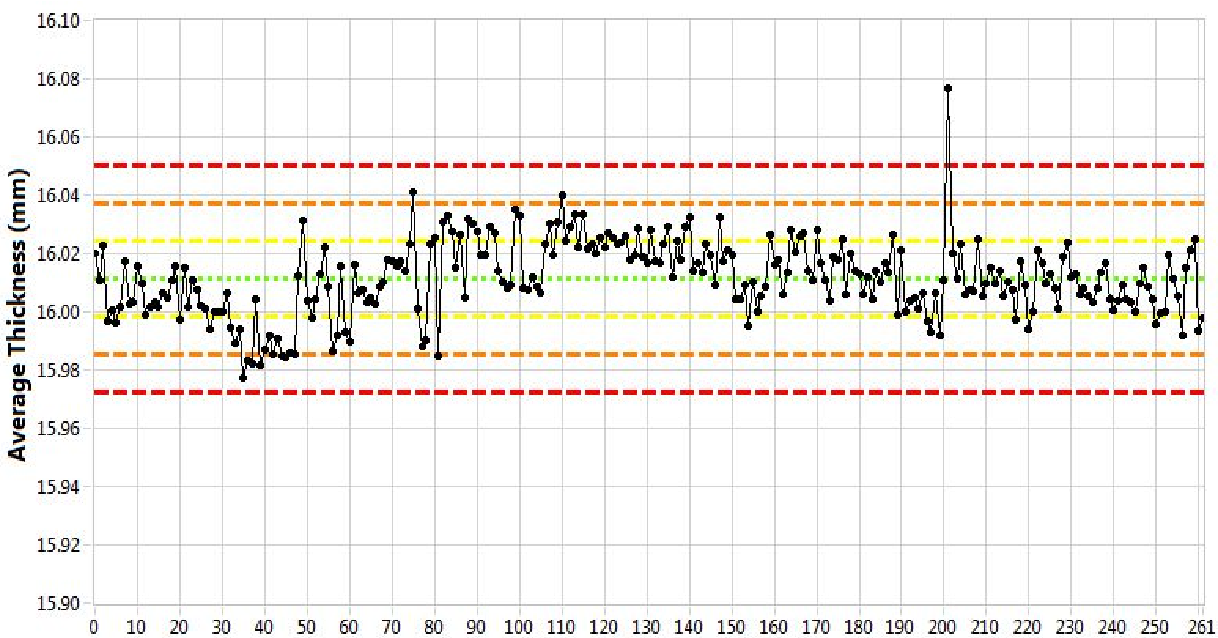


Figure B-4. Average Thickness (mm), mean = 16.011, standard deviation = 0.013.

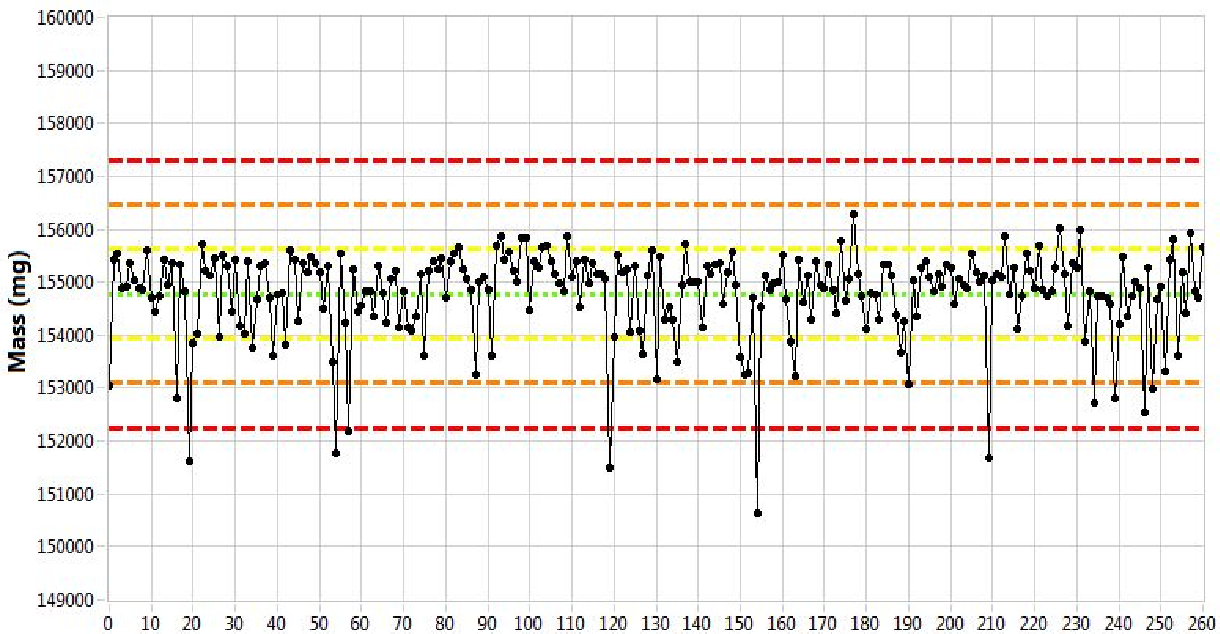


Figure B-5. Mass (mg), mean = 154776.7, standard deviation = 841.7.

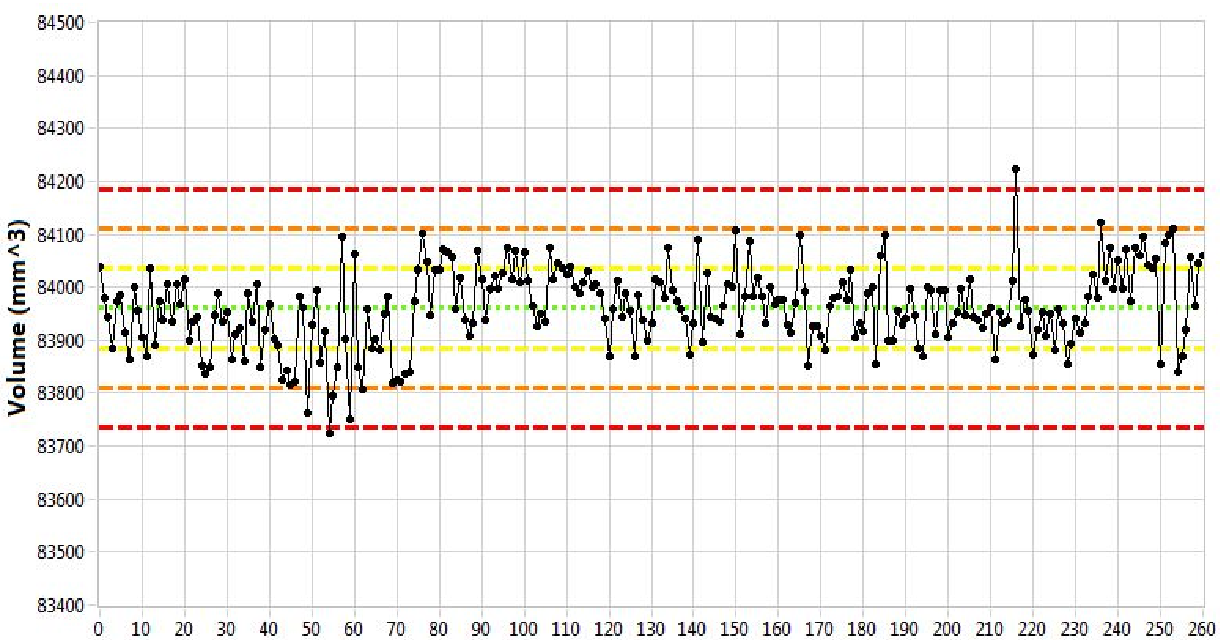


Figure B-6. Volume (mm^3), mean = 83961, standard deviation = 74.8.

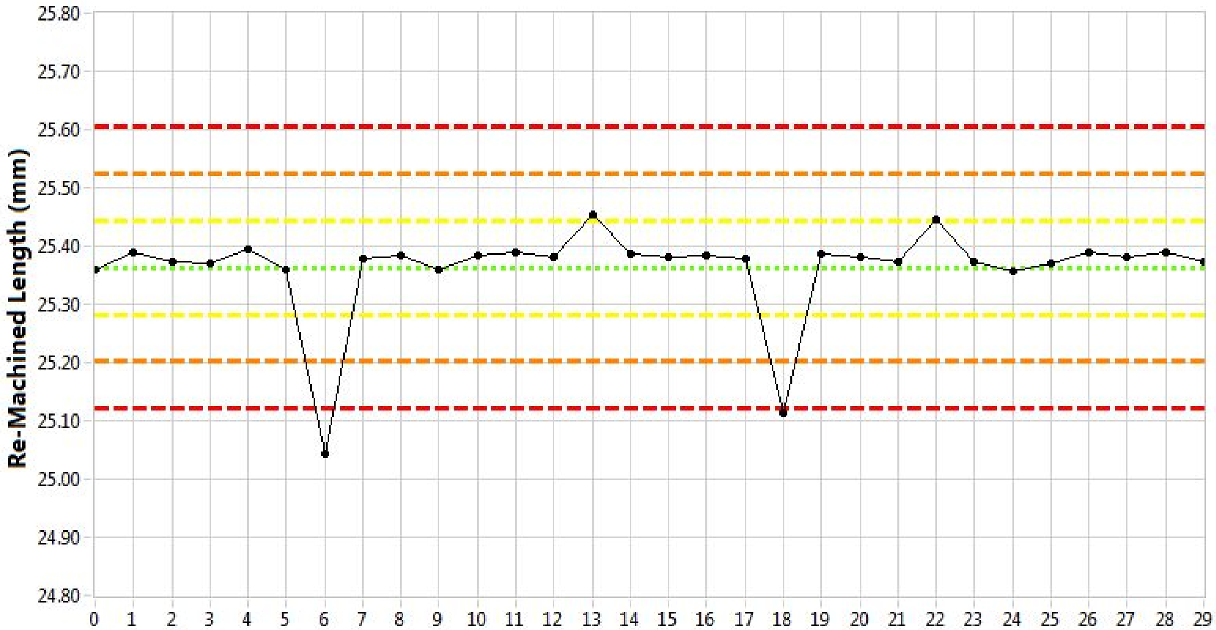


Figure B-7. Re-machined creep specimen length (mm), mean = 25.3630, standard deviation = 0.0808.

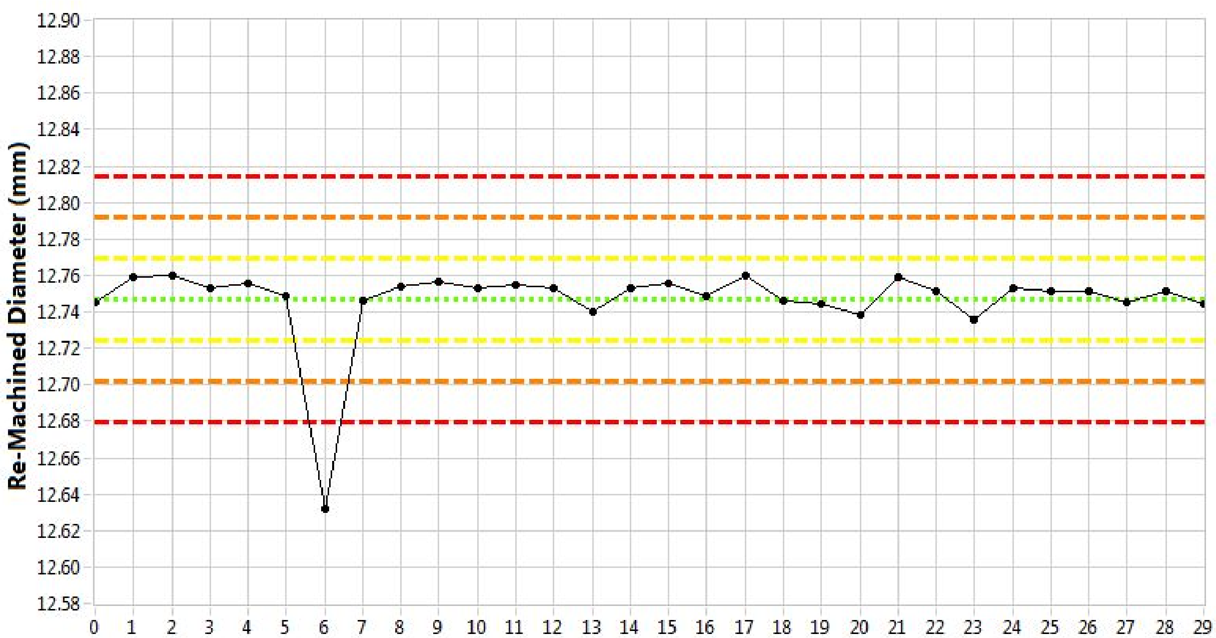


Figure B-8. Re-machined creep specimen diameter (mm), mean = 12.7467, standard deviation = 0.0225.

Title: Baseline Characterization Database Verification Report – NBG-18 Billet 635-4

ECAR No.: 3677 Rev. No.: 0 Project No.: 32138 Date: 07/12/2017

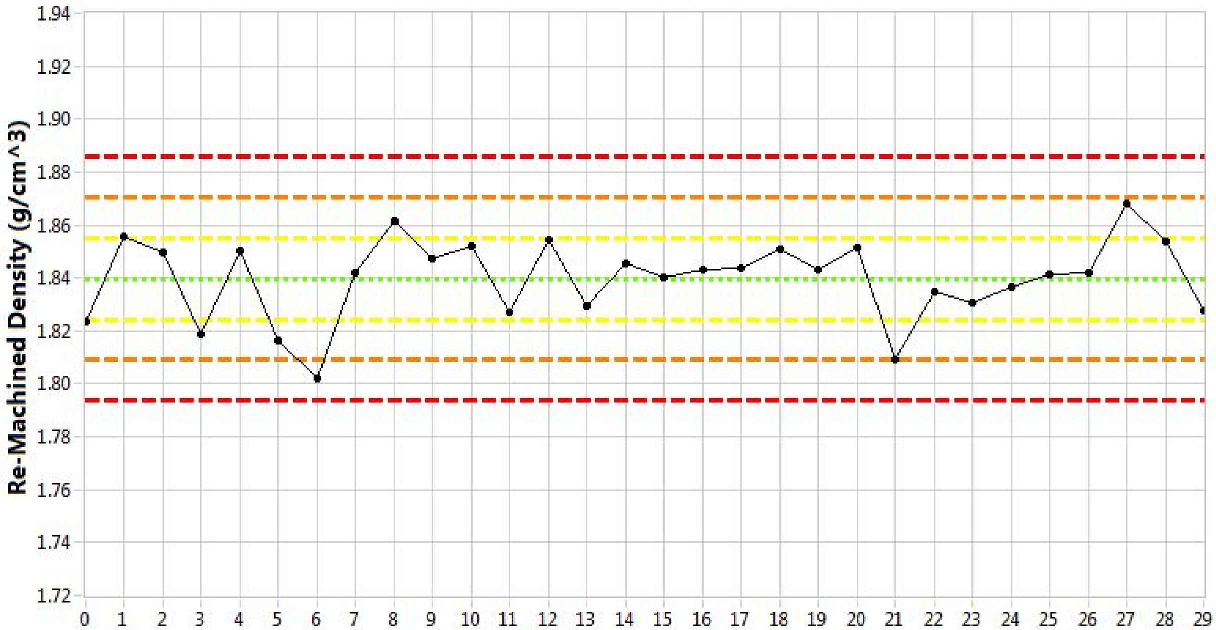


Figure B-9. Re-machined creep specimen density (g/cm^3), mean = 1.8397, standard deviation = 0.0153.

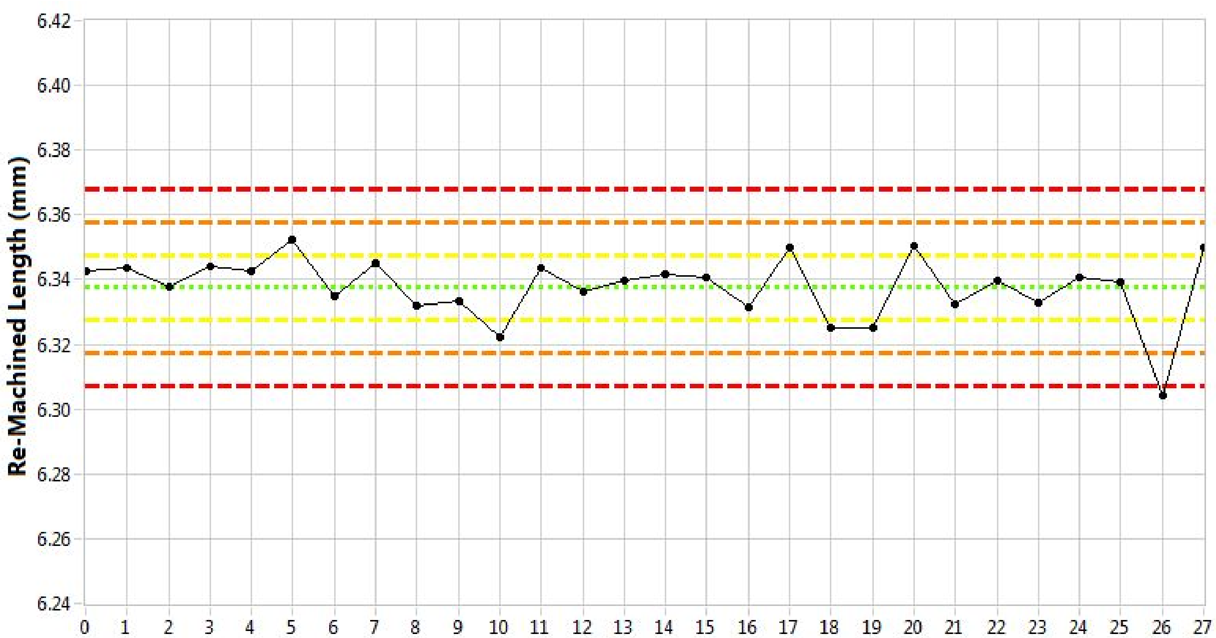


Figure B-10. Re-machined piggyback length (mm), mean = 6.3376, standard deviation = 0.0102.

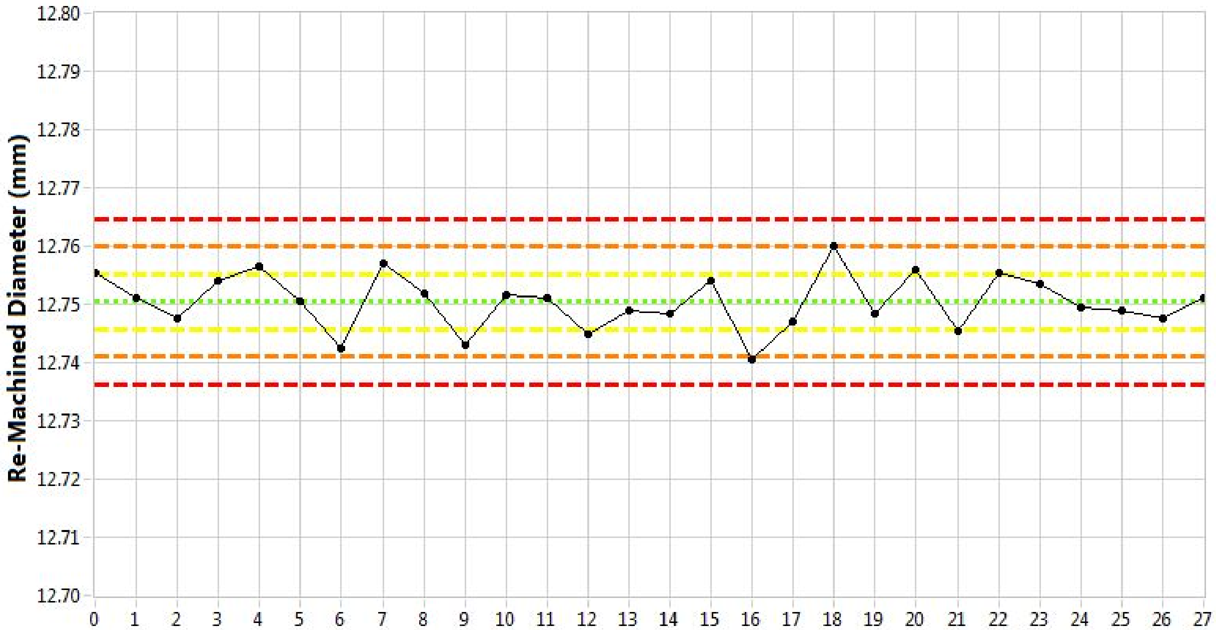


Figure B-11. Re-machined piggyback diameter (mm), mean = 12.7504, standard deviation = 0.0047.

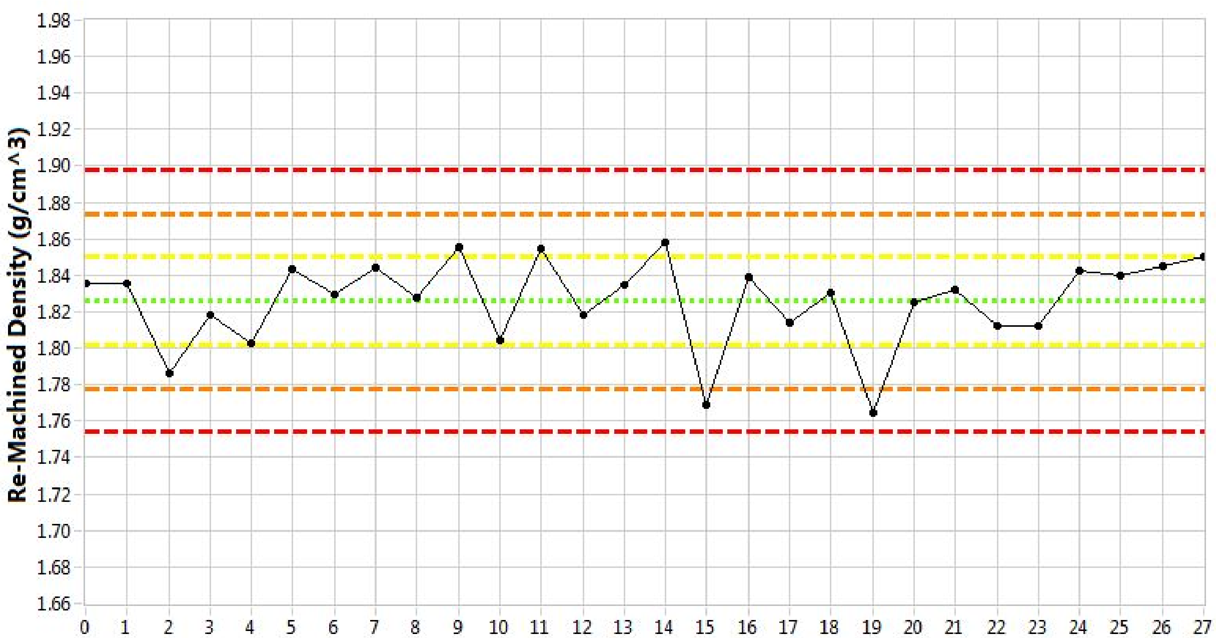


Figure B-12. Re-machined piggyback density (g/cm^3), mean = 1.8259, standard deviation = 0.0240.

Appendix C

Additional Tensile Specimen Database Plots (NBG-18 635-4T)

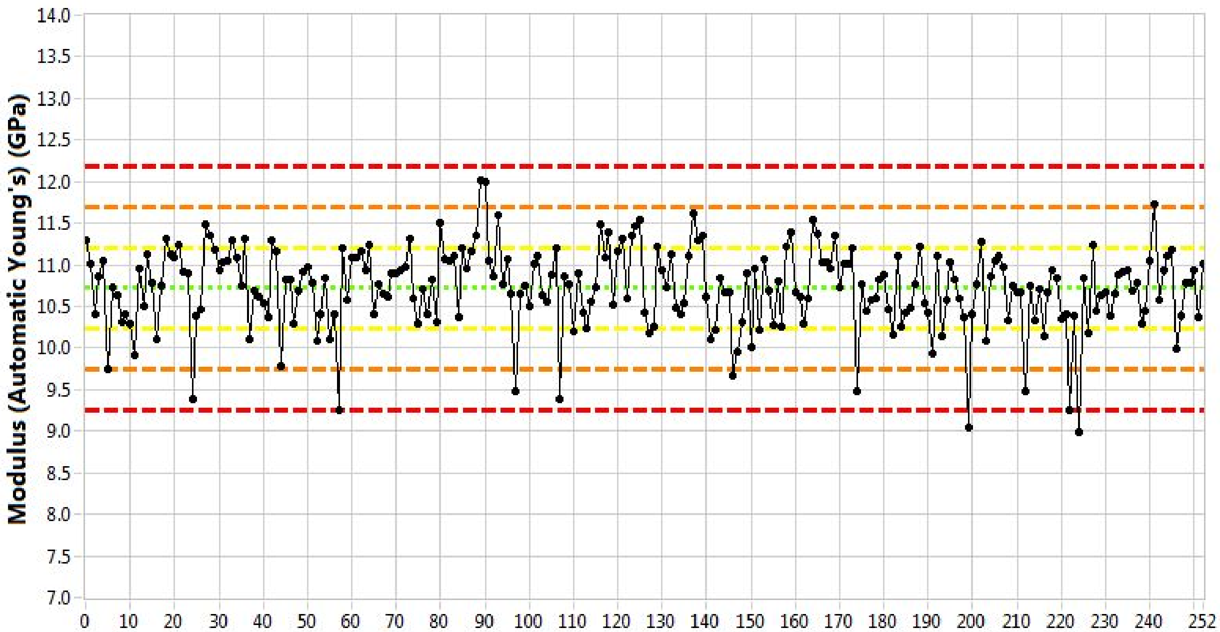


Figure C-1. Modulus (automatic Young's) (GPa), mean = 10.7, standard deviation = 0.49.

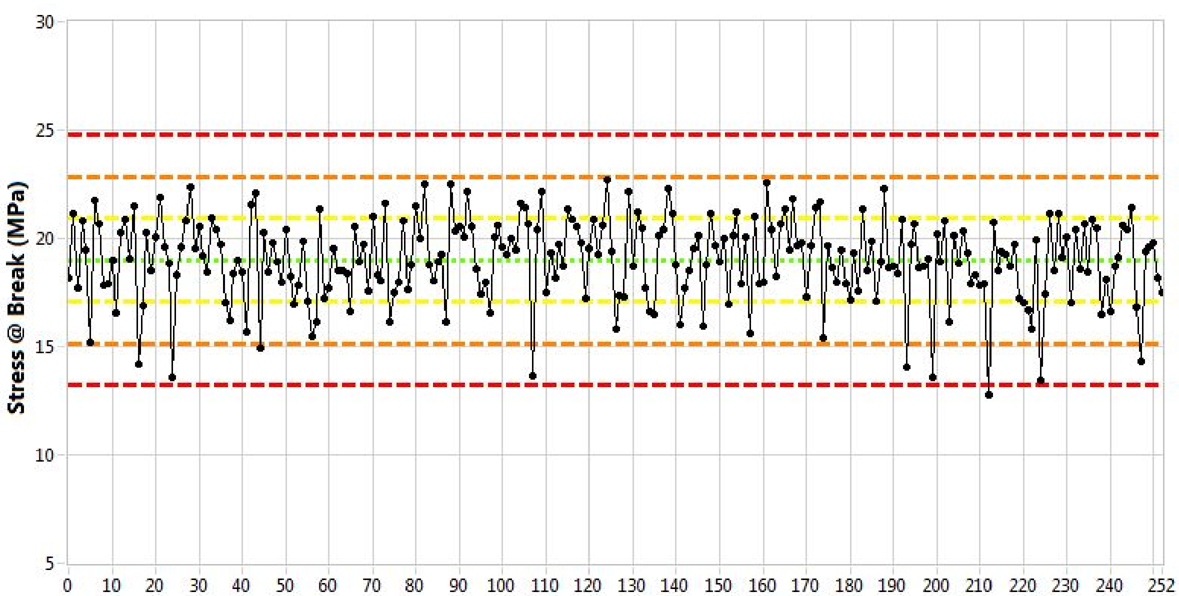


Figure C-2. Stress at break (MPa), mean = 19.0, standard deviation = 1.9.

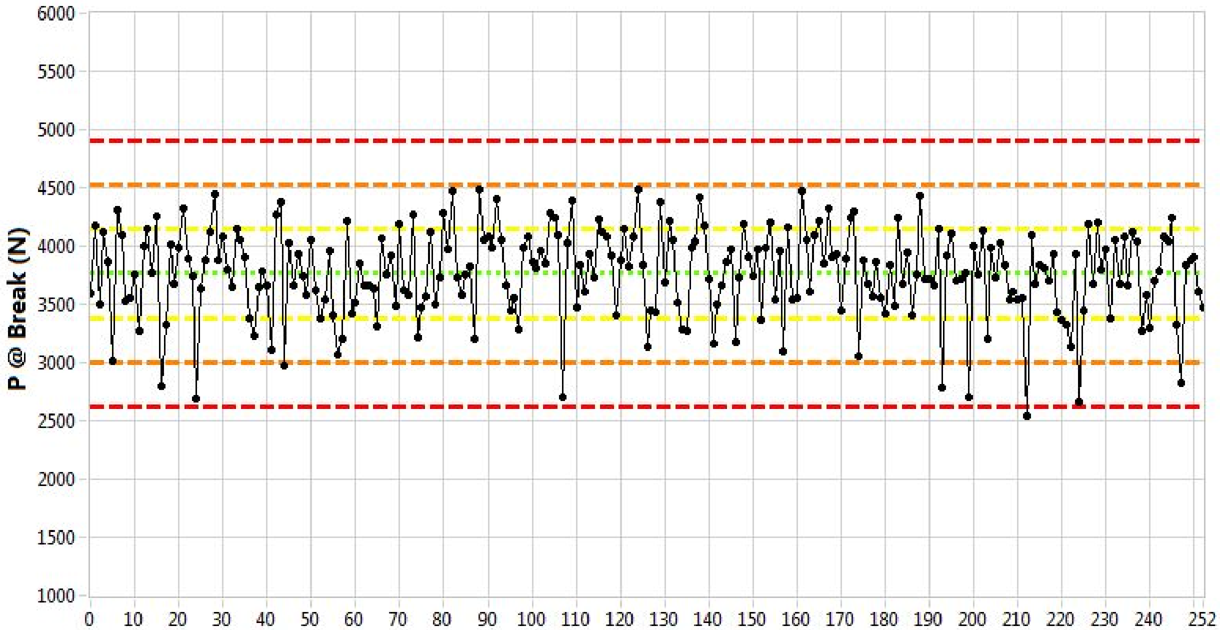


Figure C-3. Load at break (N), mean = 3,766, standard deviation = 382.

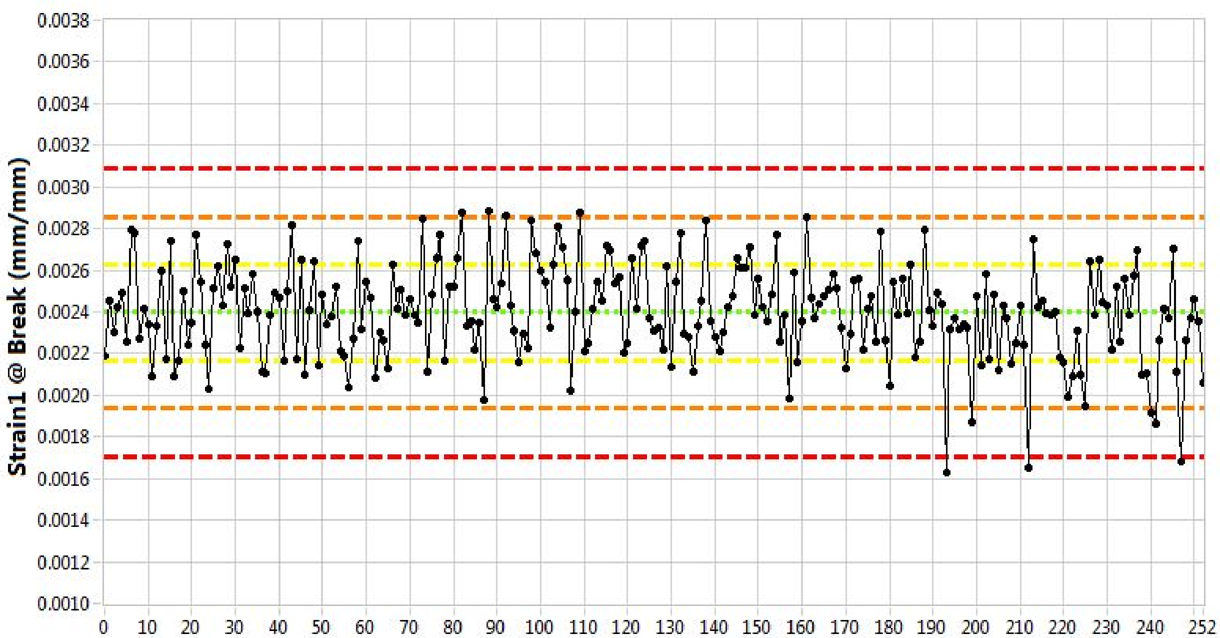


Figure C-4. Strain 1 at break (mm/mm), mean = 0.0024, standard deviation = 0.00023.

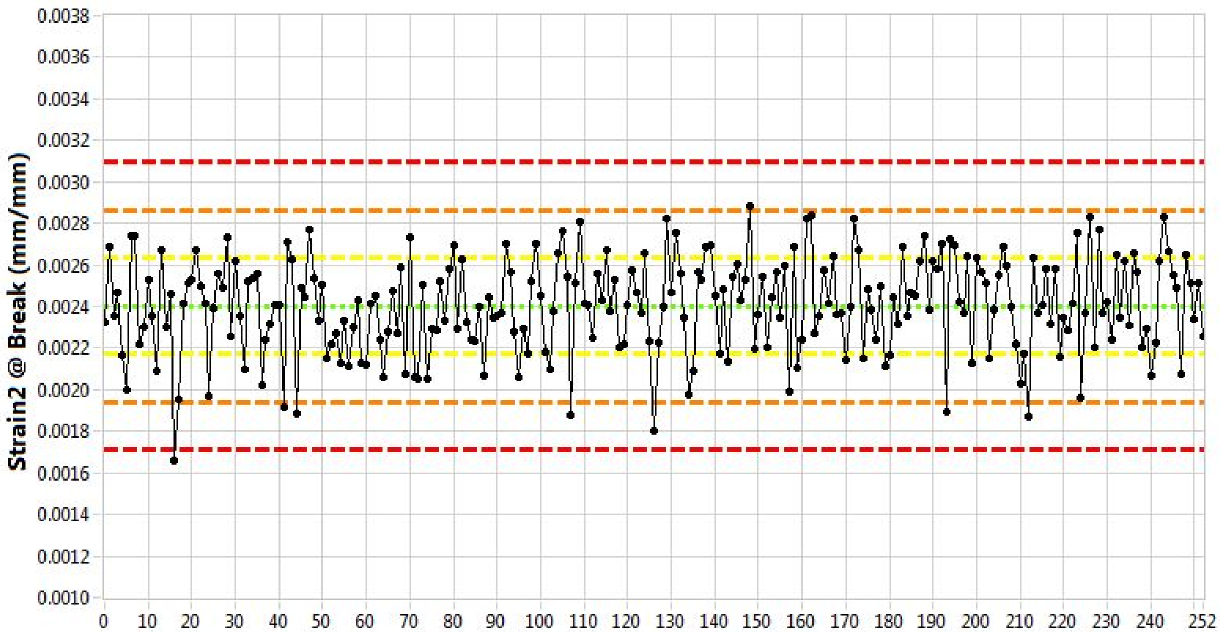


Figure C-5. Strain 2 at break (mm/mm), mean = 0.0024, standard deviation = 0.00023.

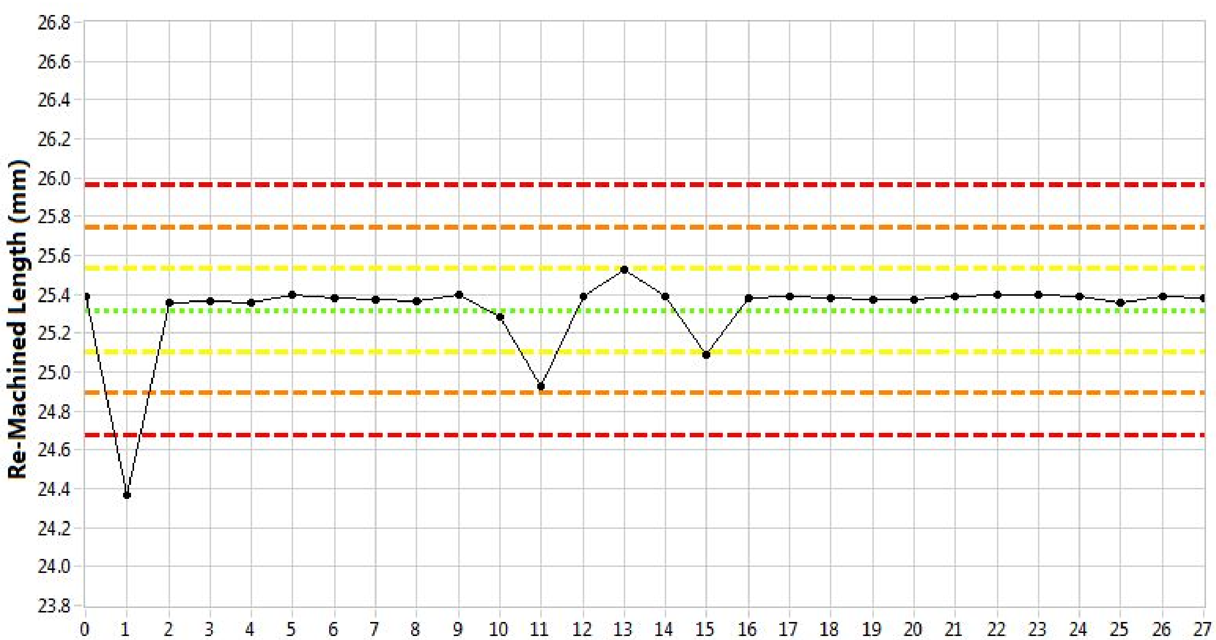


Figure C-6. Re-machined creep specimen length (mm), mean = 25.3198, standard deviation = 0.2142.

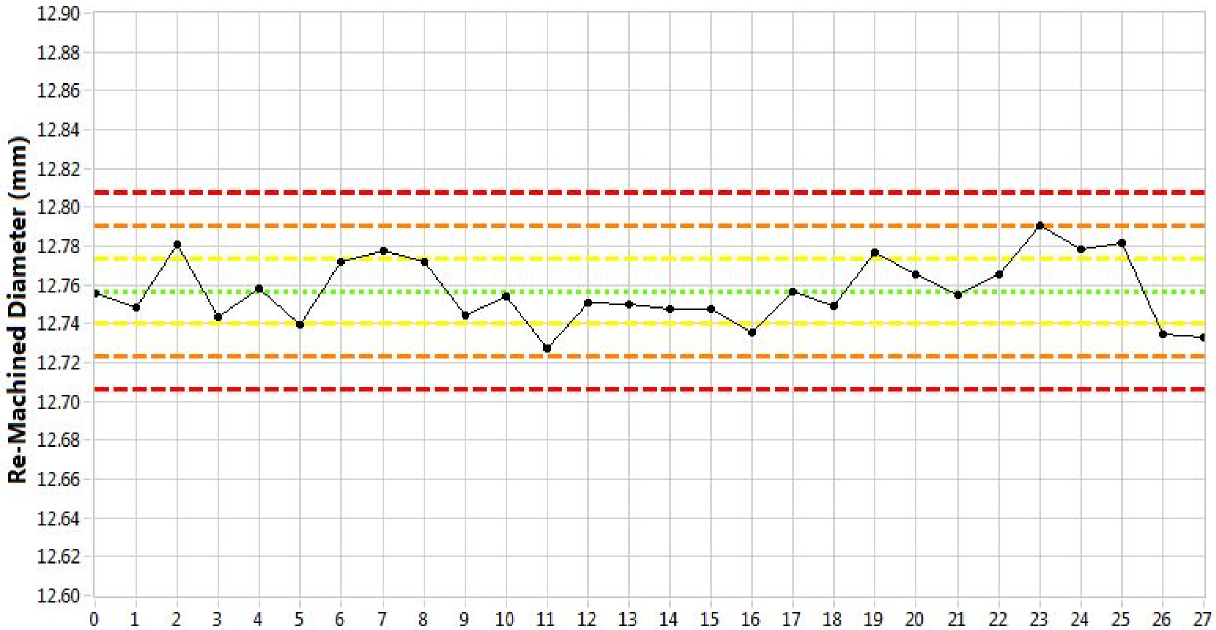


Figure C-7. Re-machined creep specimen diameter (mm), mean = 12.7569, standard deviation = 0.0168.

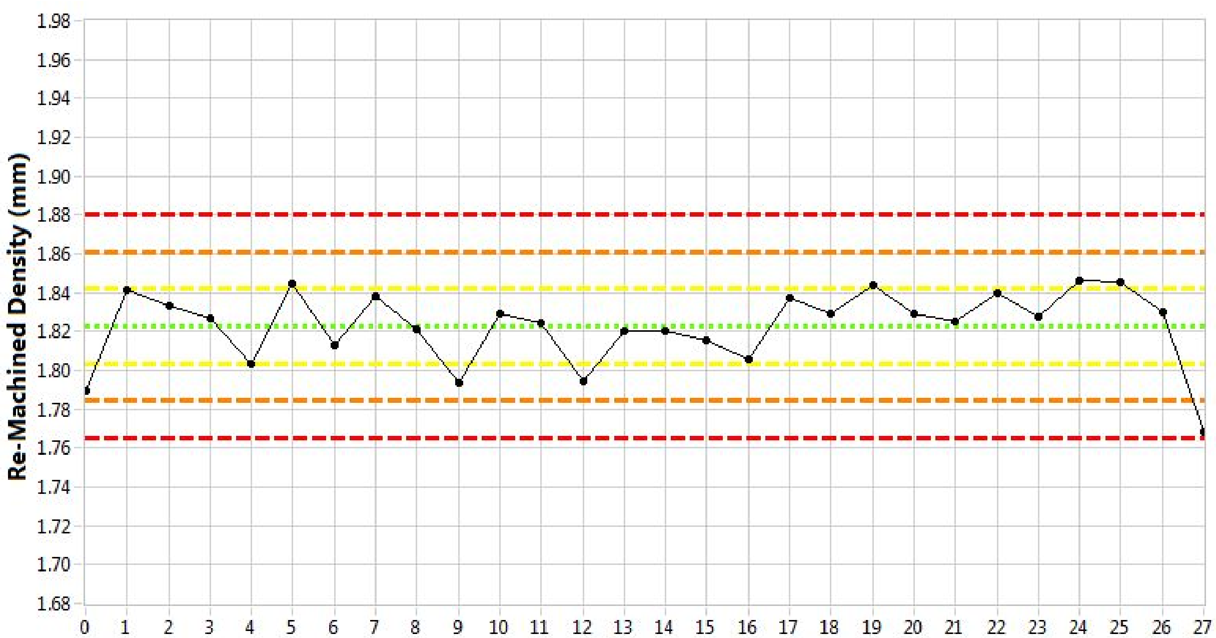


Figure C-8. Re-machined creep specimen density (g/cm^3), mean = 1.8227, standard deviation = 0.0192.

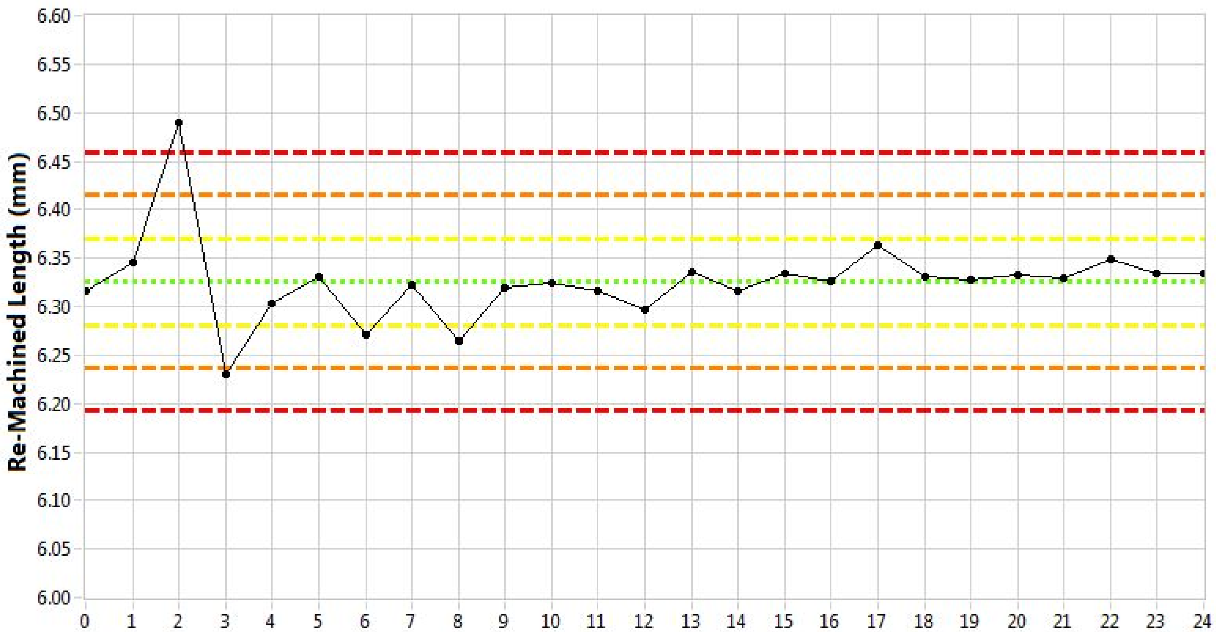


Figure C-9. Re-machined piggyback specimen length (mm), mean = 6.3258, standard deviation = 0.0444.

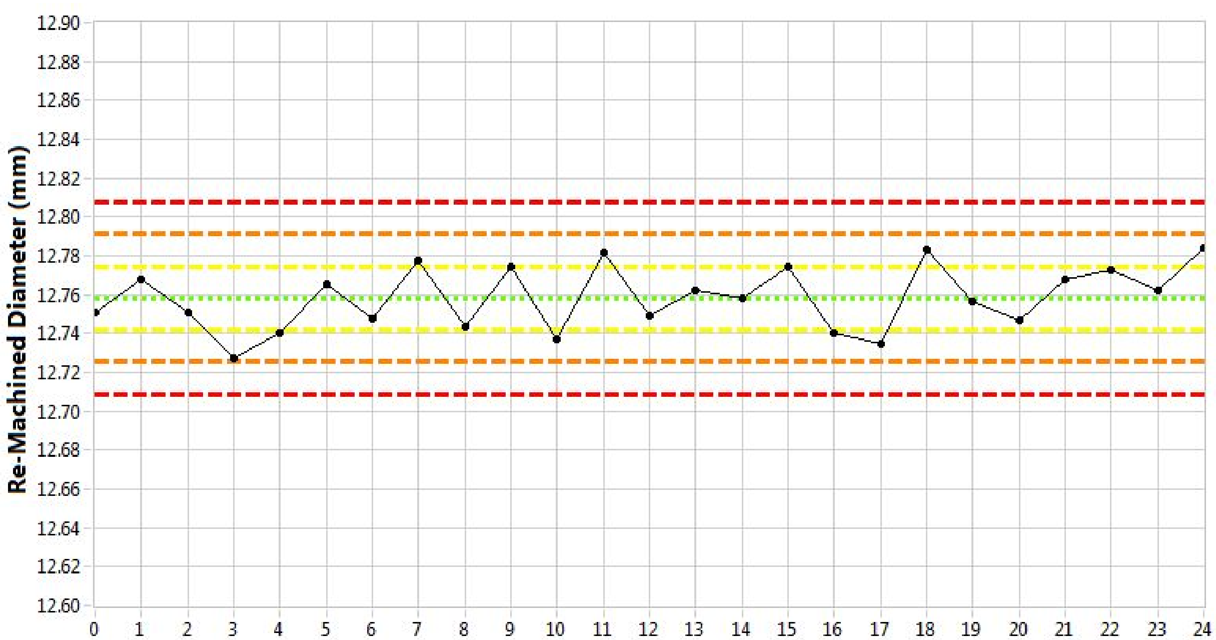


Figure C-10. Re-machined piggyback specimen diameter (mm), mean = 12.7582, standard deviation = 0.0164.

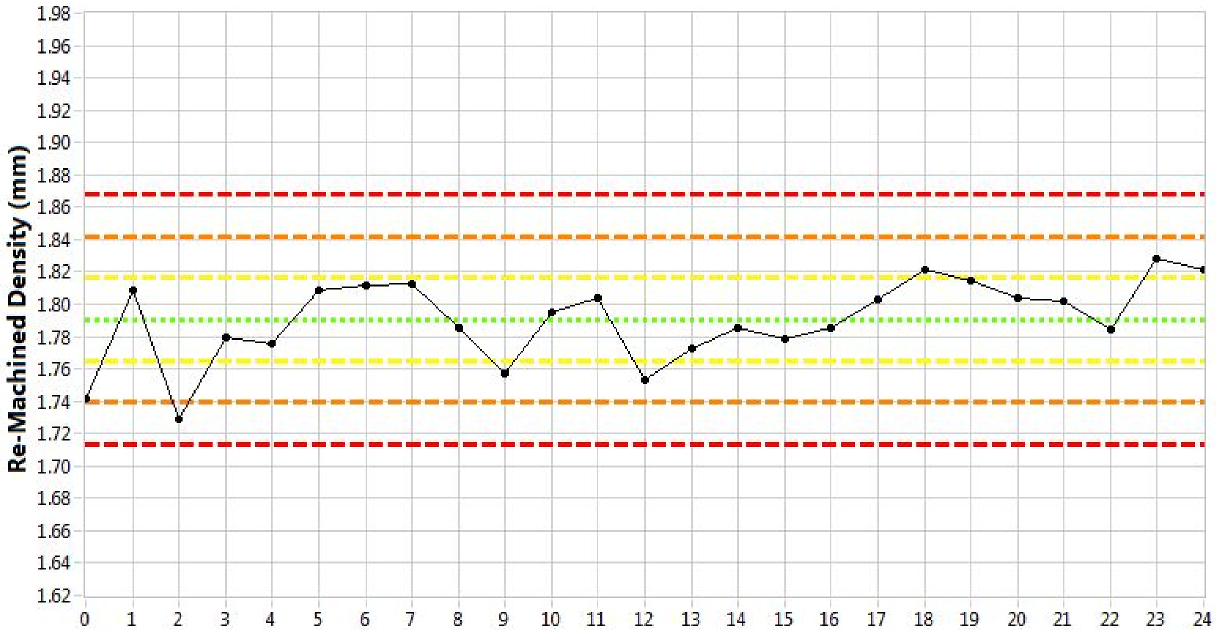


Figure C-11. Re-machined piggyback specimen density (g/cm^3), mean = 1.7906, standard deviation = 0.0257.

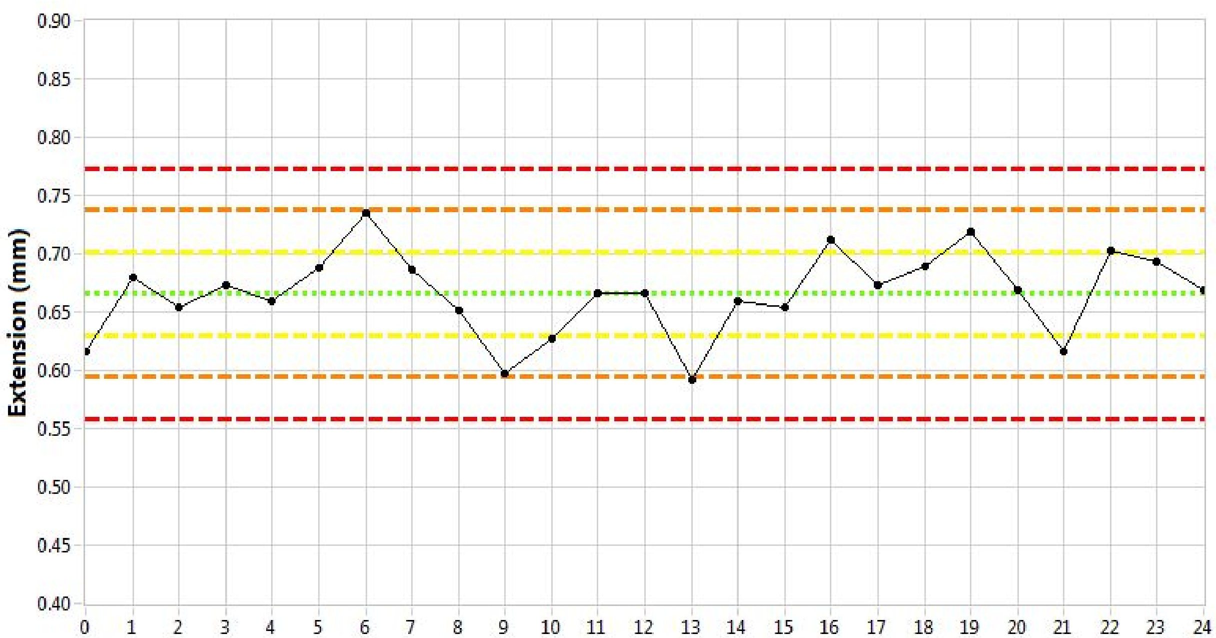


Figure C-12. Split disc extension (mm), mean = 0.6659, standard deviation = 0.0358.

Title: Baseline Characterization Database Verification Report – NBG-18 Billet 635-4

ECAR No.: 3677 Rev. No.: 0 Project No.: 32138 Date: 07/12/2017

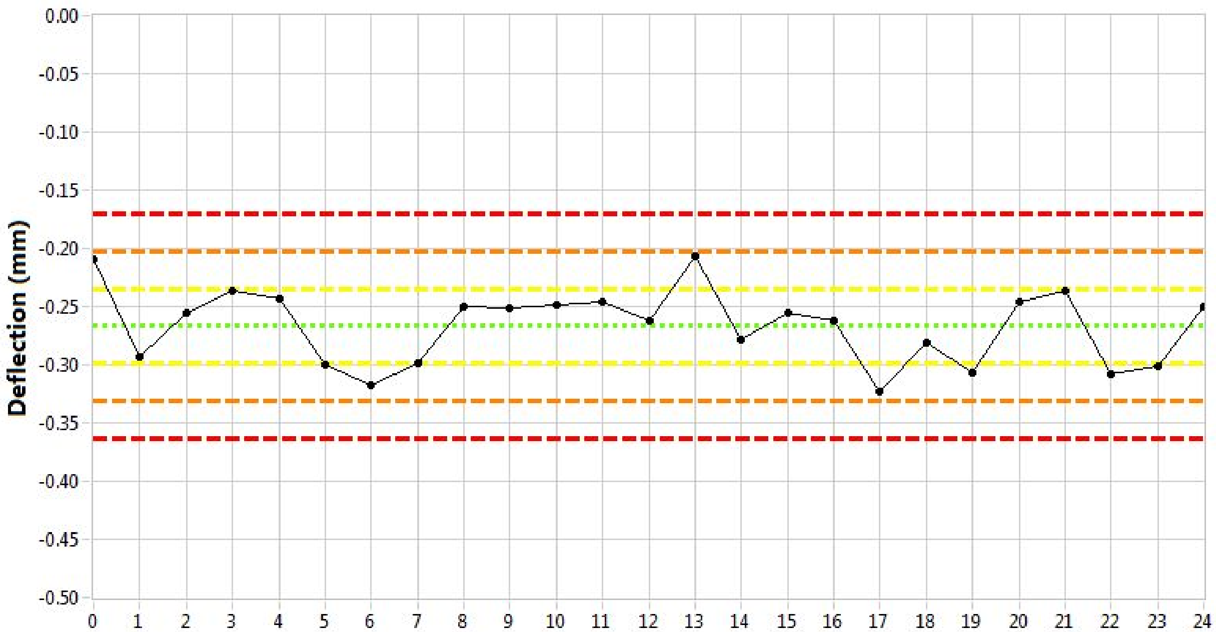


Figure C-13. Split disc deflection (mm), mean = -0.2667, standard deviation = 0.0322.