

HDG-1 Graphite Pre-Irradiation Data Package Report

INL/EXT-20-59175
Revision 1

Advanced Reactor Technologies

APRIL 2025

Dave Rohrbaugh, Will Windes, W. David Swank

Idaho National Laboratory



DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

HDG-1 Graphite Pre-Irradiation Data Package Report

Dave Rohrbaugh, Will Windes, W. David Swank
Idaho National Laboratory

April 2025

Idaho National Laboratory
Advanced Reactor Technologies
Idaho Falls, Idaho 83415

<http://www.art.inl.gov>

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

Page intentionally left blank

INL ART Program
HDG-1 Graphite Pre-Irradiation Data Package Report

INL/EXT-20-59175
Revision 1

April 2025

Technical Reviewer: (Confirmation of mathematical accuracy, correctness of data, and appropriateness of assumptions.)

Austin Matthews

04/03/2025

Austin Matthews
INL ART Graphite Engineer

Approved by:

Kip Kloimonhagen

04/08/2025

William E. Windes (delegated authority)
INL ART Graphite R&D Technical Lead

Date

Travis Mitchell

04/03/2025

Travis R. Mitchell
ART Program Manager

Date

Michelle T. Sharp

Michelle T. Sharp
INL Quality Assurance

4/3/2025

Date

Page intentionally left blank

SUMMARY

This report documents all pre-irradiation examination material-property measurement data for graphite specimens that are going to be used in the High Dose Graphite-1 (HDG-1) irradiation capsule. The two new HDG capsules signify a major change to the Advanced Graphite Creep (AGC) experiment.

HDG-1 and HDG-2 will replace the last two AGC capsules (AGC-5 and AGC-6), which were designed to irradiate graphite at the extreme upper operational temperatures (1,100°C outlet temperature) of very-high-temperature reactor (VHTR) designs. These very-high-temperature AGC-5 and AGC-6 capsules were repurposed for re-irradiated specimens (from AGC-2, AGC-3, and AGC-4) at lower temperatures of 600 and 800°C. HDG-1 will be irradiated at 600°C, and HDG-2 will be irradiated at 800°C. By re-irradiating the previous AGC specimens, a total maximum neutron dose of around 15 dpa can be achieved for all major graphite grades at irradiation temperatures of 600 and 800°C.

Specimens in the HDG-1 capsule are composed of previously irradiated specimens from the AGC-2 capsule and unirradiated specimens prepared for the now-discontinued AGC-5 capsule. In utilizing the irradiated specimens, a maximum neutron dose of around 15 dpa is anticipated. These new maximum dose levels will provide irradiated material property data over a total neutron dose range of 1–15 dpa at a temperature of 600°C when combined with the previous AGC-1 and AGC-2 irradiation data, affording the quantitative data necessary to predict the irradiation behavior and operating performance of new nuclear graphite grades for use in high-temperature reactor designs.

Similar to previous AGC test trains, HDG-1 includes the major graphite grades (IG-110, NBG-17, NBG-18, PCEA, and 2114), but it also adds the very fine-grain grade IG-430, which is of interest to molten-salt reactor designs. Also new to the HDG-1 capsule are 90 smaller geometry specimens designated as “pencil specimens.” These specimens take up only one-third the space of a standard size creep specimen. The increased number of specimens will enhance property measurement statistics by tripling the amount of control specimen data at a position otherwise affording only a single measurement.

Page intentionally left blank

CONTENTS

SUMMARY	vii
ACRONYMS.....	xvi
1. INTRODUCTION.....	1
2. AGC EXPERIMENT DESCRIPTION.....	2
2.1. Background Information on the AGC Experiment	2
2.2. Description of HDG-1 Test Specimens.....	5
2.2.1. Graphite Specimens	5
2.2.2. Flux Wires.....	8
2.2.3. HOPG Specimens	10
2.2.4. Arrangement and Shipping of HDG-1 Specimen Stacks	10
2.2.5. Expected Dose.....	10
3. MATERIAL PROPERTY MEASUREMENTS	12
3.1. Calibration and Functional Validation	13
3.2. Mass, Dimensions, and Bulk Density	13
3.3. Electrical Resistivity	13
3.4. Approximation of Elastic Modulus from the Measurement of Sonic Velocity	14
3.5. Modulus of Elasticity by Measurement of Fundamental Frequency	17
3.6. Thermal Expansion	18
3.7. Thermal Diffusivity.....	19
4. DATA ANALYSIS.....	20
4.1. Mass, Dimensions, and Density Data Analysis	21
4.2. Electrical Resistivity	21
4.3. Approximation of Elastic Modulus from the Measurement of Sonic Velocity	22
4.4. Modulus of Elasticity by Measurement of Fundamental Frequency	23
4.5. Thermal Expansion	24
4.6. Thermal Diffusivity.....	26
5. REFERENCES.....	27
Appendix A HDG-1 Pre-Irradiation Pencil Specimen Data	29
Appendix B Summary of Statistical Parameters.....	49
Appendix C Final Loading Configuration for HDG-1 Specimens	57
Appendix D Dose Profiles for HDG-1 Specimens	75

FIGURES

Figure 1. Original (2005–2017) design of the AGC experiment, illustrating planned dose levels and irradiation temperatures for all six irradiation test capsules in support of a very-high-temperature reactor (VHTR) design (1,100°C outlet temperature).....	3
Figure 2. New graphite irradiation plan with high-dose graphite irradiations illustrating a lower-temperature, higher-dose irradiation plan.	4
Figure 3. HDG-1 pencil specimen can, ref. DWG-605048.....	7
Figure 4. Estimated dose profiles for loaded and unloaded 2114 specimens.	11
Figure 5. Electrical resistivity measurement station.	14
Figure 6. Sonic velocity measurement station.	15
Figure 7. Sonic velocity measurement user interface.	16
Figure 8. Fundamental frequency measurement station.	17
Figure 9. Commercial push-rod dilatometer for measuring CTE.	19
Figure 10. LFA measurement station for determining thermal diffusivity.	20
Figure 11. Electrical resistivity of pencil specimens of the major graphite grades.....	22
Figure 12. Young’s modulus using the sonic velocity technique vs. density for IG-430.	23
Figure 13. Young’s modulus calculated by the fundamental frequency method for the major graphite grades.....	24
Figure 14. Mean CTE for all grades of graphite in HDG-1 as a function of temperature.	25
Figure 15. Mean CTE at 500°C along with the anisotropy ratio for pencil specimens as a function of temperature.....	25
Figure 16. Thermal diffusivity for IG-430 as a function of measurement temperature.....	26
Figure 17. Diffusivity at measurement temperature 500°C vs. density for IG-430 piggyback specimens.....	27
Figure A-1. 2114 pencil specimen length.	29
Figure A-2. IG-110 pencil specimen length.....	29
Figure A-3. IG-430 pencil specimen length.....	29
Figure A-4. NBG-17 pencil specimen length.	30
Figure A-5. NBG-18 pencil specimen length.	30
Figure A-6. PCEA pencil specimen length.....	30
Figure A-7. IG-430 piggyback specimen length.....	31
Figure A-8. 2114 pencil specimen diameter.	31
Figure A-9. IG-110 pencil specimen diameter.....	31
Figure A-10. IG-430 pencil specimen diameter.....	32
Figure A-11. NBG-17 pencil specimen diameter.	32
Figure A-12. NBG-18 pencil specimen diameter.	32

Figure A-13. PCEA pencil specimen diameter.....	33
Figure A-14. IG-430 piggyback specimen diameter.....	33
Figure A-15. 2114 pencil specimen density.....	33
Figure A-16. IG-110 pencil specimen density.....	34
Figure A-17. IG-430 pencil specimen density.....	34
Figure A-18. NBG-17 pencil specimen density.....	34
Figure A-19. NBG-18 pencil specimen density.....	35
Figure A-20. PCEA pencil specimen density.....	35
Figure A-21. IG-430 piggyback specimen density.....	35
Figure A-22. 2114 pencil specimen mass.....	36
Figure A-23. IG-110 pencil specimen mass.....	36
Figure A-24. IG-430 pencil specimen mass.....	36
Figure A-25. NBG-17 pencil specimen mass.....	37
Figure A-26. NBG-18 pencil specimen mass.....	37
Figure A-27. PCEA pencil specimen mass.....	37
Figure A-28. IG-430 piggyback specimen mass.....	38
Figure A-29. 2114 pencil specimen modulus by sonic resonance method.....	38
Figure A-30. IG-110 pencil specimen modulus by sonic resonance method.....	38
Figure A-31. IG-430 pencil specimen modulus by sonic resonance method.....	39
Figure A-32. NBG-17 pencil specimen modulus by sonic resonance method.....	39
Figure A-33. NBG-18 pencil specimen modulus by sonic resonance method.....	39
Figure A-34. PCEA pencil specimen modulus by sonic resonance method.....	40
Figure A-35. 2114 pencil specimen resistivity.....	40
Figure A-36. IG-110 pencil specimen resistivity.....	40
Figure A-37. IG-430 pencil specimen resistivity.....	41
Figure A-38. NBG-17 pencil specimen resistivity.....	41
Figure A-39. NBG-18 pencil specimen resistivity.....	41
Figure A-40. PCEA pencil specimen resistivity.....	42
Figure A-41. IG-430 piggyback Young's and shear moduli.....	42
Figure A-42. 2114 pencil specimen mean CTE at 500°C.....	43
Figure A-43. IG-110 pencil specimen mean CTE at 500°C.....	43
Figure A-44. IG-430 pencil specimen mean CTE at 500°C.....	43
Figure A-45. NBG-17 pencil specimen mean CTE at 500°C.....	44
Figure A-46. NBG-18 pencil specimen mean CTE at 500°C.....	44
Figure A-47. PCEA pencil specimen mean CTE at 500°C.....	44

Figure A-48. IG-430 piggyback specimen mean CTE at 500°C.	45
Figure A-49. IG-430 piggyback specimen diffusivity at 500°C.	45
Figure A-50. 2114 piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).	46
Figure A-51. NBG-17 piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).	46
Figure A-52. NBG-18 piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).	47
Figure A-53. NBG-25 piggyback specimen mean CTE at 500°C.	47
Figure A-54. PCEA piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).	48
Figure A-55. PCEA piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).	48
Figure D-1. IG-110 loaded specimens estimated dose profile for HDG-1.	75
Figure D-2. IG-110 unloaded specimens estimated dose profile for HDG-1.	76
Figure D-3. IG-430 loaded specimens estimated dose profile for HDG-1.	76
Figure D-4. IG-430 unloaded specimens estimated dose profile for HDG-1.	77
Figure D-5. NBG-17 loaded specimens estimated dose profile for HDG-1.	77
Figure D-6. NBG-17 unloaded specimens estimated dose profile for HDG-1.	78
Figure D-7. NBG-18 loaded specimens estimated dose profile for HDG-1.	78
Figure D-8. NBG-18 unloaded specimens estimated dose profile for HDG-1.	79
Figure D-9. PCEA loaded specimens estimated dose profile for HDG-1.	79
Figure D-10. PCEA unloaded specimens estimated dose profile for HDG-1.	80

TABLES

Table 1. Graphite grades and grain orientations within the HDG-1 capsule.	5
Table 2. Pencil can numbering and loading.	7
Table 3. Flux wire vanadium can loading for each graphite can holder.	9
Table 4. HOPG specimen dimensions.	10
Table 5. Graphite testing standards.	12
Table 6. Creep specimen length outliers.	21
Table B-1. Pencil specimen length (mm) summary statistics.	49
Table B-2. Pencil specimen diameter (mm) summary statistics.	50
Table B-3. Pencil specimen mass (g) summary statistics.	51
Table B-4. Pencil specimen density (g/cm ³) summary statistics.	52
Table B-5. Creep specimen coefficient of thermal expansion (1/K) at 500°C summary statistics.	53

Table B-6. Pencil specimen modulus (GPa) by sonic resonance summary statistics.	54
Table B-7. Pencil specimen resistivity (mW-m) summary statistics.	55
Table B-8. IG-430 piggyback specimen summary statistics.....	56
Table B-9. Piggyback specimen coefficient of thermal expansion (1/K) at 500°C summary statistics.	56
Table C-1. Final loading configuration for HDG-1 specimens. The height (inches) is the distance from the reactor core centerline to the specimen’s center of mass.	57

Page intentionally left blank

ACRONYMS

AGC	advanced graphite creep
AGC-1	first advanced graphite capsule
ART	advanced reactor technology
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
COV	coefficient of variation
CTE	coefficient of thermal expansion
HDG	high-dose graphite
HOPG	highly oriented pyrolytic graphite
HTR	high-temperature reactor
INL	Idaho National Laboratory
IQR	interquartile range
LFA	laser flash apparatus
PIE	post-irradiation examination
VHTR	very-high-temperature reactor

Page intentionally left blank

HDG-1 Graphite Pre-Irradiation Data Package Report

1. INTRODUCTION

The Advanced Reactor Technology (ART) Graphite Research and Development Program is conducting an extensive graphite irradiation program to provide data for licensing high-temperature reactor (HTR) designs. In past applications, graphite was used effectively as a structural and moderator material in both research and commercial high-temperature gas-cooled reactor designs.¹ Nuclear graphite H-451, previously used in the U.S. for nuclear reactor graphite components, is no longer available. New nuclear graphite grades have been developed as suitable candidates for new HTR reactor designs. To support the design and licensing of new HTR core components for commercial reactors, a complete material properties database must be developed for these new grades of graphite. Quantitative data on in-service material performance is required for the physical, mechanical, and thermal properties of each major graphite grade, with a specific emphasis on data that accounts for the life-limiting effects of irradiation creep on key physical properties of these HTR-candidate graphite grades. Further details on R&D activities and the associated rationale for qualifying nuclear-grade graphite for use in HTRs are documented in the Graphite Technology Development Plan.^{2,3}

Based on experiences with previous graphite-core components, the phenomenon of irradiation-induced creep within the graphite has proven critical in calculating 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. Significant internal stresses within these components can result from a second phenomenon—irradiation-induced dimensional change—in which the graphite physically changes (i.e., first shrinking, then expanding with increasing neutron dose). This disparity in material volume change can produce significant internal stresses within graphite components. Irradiation-induced creep relaxes these large internal stresses, reducing the risk of crack formation and component failure. Higher irradiation-creep levels tend to relieve more internal stress, thus allowing the components longer useful lifetimes within the core. Measuring the irradiation-creep rates of nuclear-grade graphite is therefore critical for determining the useful lifetime of graphite reactor components and is a major part of the Advanced Graphite Creep (AGC) experiment.

The AGC experiment is currently underway to determine the in-service behavior of these new graphite grades for HTR and molten-salt reactor designs. This experiment will examine the properties and behavior of nuclear-grade graphite over a large spectrum of temperatures, irradiation fluences, and applied stress levels expected to cause irradiation creep strains within HTR graphite components.

Irradiation data are provided through the AGC test series, consisting of six planned capsules irradiated in a large flux trap in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). Each irradiation capsule consists of over 400 graphite specimens characterized before and after irradiation to determine the irradiation-induced material property changes and life-limiting irradiation creep rate for each graphite grade.

Irradiation creep is typically determined by calculating the difference between the dimensional change occurring within creep specimens under an applied stress to that of control specimens that are not stressed while being exposed to the same irradiation dose and temperature. To achieve this, detailed analyses of the reactor flux profile and the designed loading configurations within the capsule are both required to map each specimen's position. Such mapping ensures that the creep and control specimens experience the same irradiation temperature and dose levels. Details on the specimen loading order, the loading design of the capsule, the flux profile within the ATR, and the resulting estimated dose profiles for each graphite specimen are discussed within this pre-irradiation data analysis report.

2. AGC EXPERIMENT DESCRIPTION

The AGC experiment is designed to establish the data necessary for determining the safe operating envelope of HTR graphite core components by measuring irradiated material property changes and the behavior of several new nuclear graphite grades over a range of temperatures, neutron fluence levels, and mechanical compressive loads. The experiment consists of three interrelated stages: pre-irradiation characterization of the graphite specimens, the irradiation test series (designated as six separate irradiation test-train capsules), and post-irradiation examination (PIE)/analysis. Separate reports on each distinctive stage are prepared once each individual activity is complete.

The pre-irradiation examination reports detail the total number of graphite types and specimens, the loading configuration for exposing all specimens to the entire range of irradiation conditions, and pre-irradiation material property testing results. The test series as-run irradiation reports detail the irradiation history of each capsule while in the reactor, noting any changes from the technical and functional specifications of each specific test series capsule and identifying possible improvements to the next test series capsule design. The PIE reports detail changes in the specimen material-property measurements, compare the results to pre-irradiation examination material property measurements, and analyze the data to help determine credible safe operating limits for graphite core components in HTR design and licensing applications.

2.1. Background Information on the AGC Experiment

The AGC experiment will provide irradiated material property data for graphite types currently available for use in HTR designs. Due to the volume limitations of typical material test reactors (i.e., the ATR), only a limited number of specimens can be irradiated—far fewer than what is needed for an accurate statistical specimen population analysis. Therefore, the AGC experiments only measure the irradiated material property changes and behavior of relatively few specimens of new nuclear graphite grades over the anticipated operating temperature range, neutron fluences, and mechanical loads. The experiment does generate quantitative material-property change data (and limited irradiation-creep data) that will be used in conjunction with the as-fabricated material property measurement program (baseline program) to predict the in-service behavior and operating performance of these new nuclear graphite grades for pebble-bed and prismatic reactor designs. Changes to key thermal, physical, and mechanical material properties are determined by comparing the material properties of each specimen before and after irradiation. Measured differences between these irradiation conditions will provide irradiation behavior data for graphite, with a specific emphasis on data that accounts for the life-limiting effects of irradiation creep on key physical properties of several HTR-candidate graphite grades.

The core of the AGC experiment is the irradiation test series, comprised of six planned irradiation capsules irradiated in a large flux trap in the ATR, as described in the Graphite Technology Development Plan.² This test series exposes test specimens of selected nuclear-grade graphite types to the sorts of temperature and dose ranges expected in HTR designs. Originally, graphite specimens were to be exposed to a fast-neutron dose ($E > 0.1$ MeV) of 1–7 dpa along with temperatures of 600, 800, and 1,100°C Figure 1. AGC-1 and AGC-2 were designed to be irradiated within the South Flux Trap, while AGC-3 and AGC-4 were irradiated within the ATR’s East Flux Trap. AGC-1 and AGC-4 were irradiated for approximately twice as long within the ATR as AGC-2 and AGC-3, respectively.

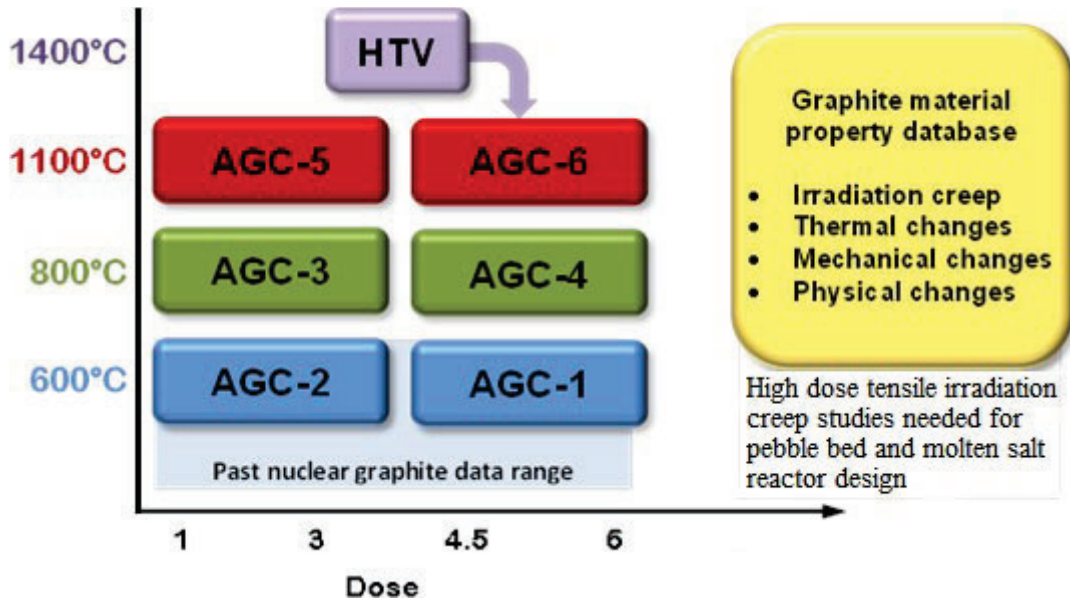


Figure 1. Original (2005–2017) design of the AGC experiment, illustrating planned dose levels and irradiation temperatures for all six irradiation test capsules in support of a very-high-temperature reactor (VHTR) design (1,100°C outlet temperature).

In 2018, the Department of Energy (DOE) ART graphite program approved a major design change to the AGC experiment, extending the neutron dose range from 0–7 dpa to 0–15 dpa—a dose range more pertinent to current HTR designs. This neutron dose increase will extend current nuclear grades past turnaround dose levels and into a non-linear (tertiary) creep regime. To achieve this higher maximum dose level, the last two irradiation capsules, AGC-5 and AGC-6, were repurposed for irradiation at VHTR conditions of 1,100°C. Under the new direction (2018), the AGC-5 and AGC-6 capsules will be used to irradiate previously exposed specimens from AGC-2, AGC-3, and AGC-4 once they have undergone PIE (see Figure 2). AGC-5 will be renamed “High Dose Graphite-1” (HDG-1) and will re-irradiate AGC-2 specimens at a nominal irradiation temperature of 600°C. AGC-6 will be renamed “HDG-2” and will re-irradiate selected specimens from AGC-3 and AGC-4 at a nominal irradiation temperature of 800°C. No graphite specimens will be irradiated at temperatures of 1,100°C. Once irradiation is complete in HDG-1 and HDG-2, all specimens will undergo a second PIE testing to determine how this higher dose level affects material properties.

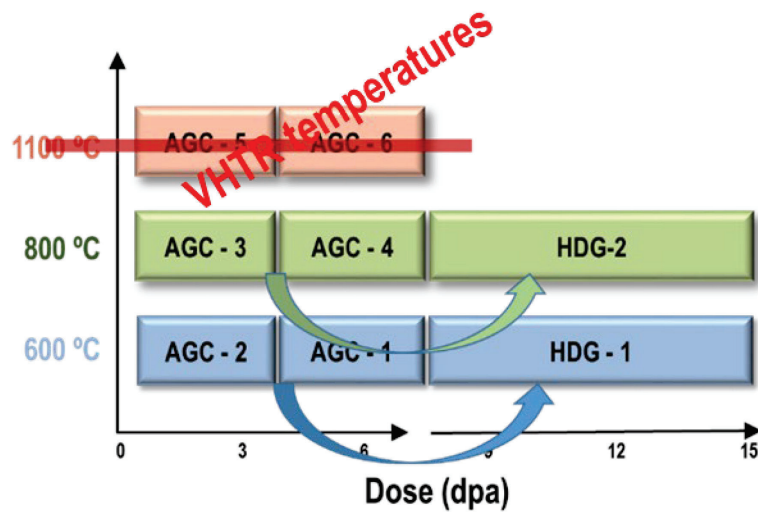


Figure 2. New graphite irradiation plan with high-dose graphite irradiations illustrating a lower-temperature, higher-dose irradiation plan.

This change did not affect the AGC-3 or AGC-4 irradiations and PIE. Thus, no changes were made to the capsule design, specimen testing, or PIE analysis on the initial 0–7 dpa, 600 and 800°C irradiations. Design, fabrication, and assembly of the HDG-1 capsule was similar in all aspects to previous AGC capsules, with the one exception of handling activated specimens from the AGC-2 test train. The HDG-1 specimen loading order was carefully designed to ensure that each previously irradiated specimen received a mechanical loading similar to that experienced in the AGC-2 test train (i.e., unloaded specimens remained unloaded and stressed specimens had the same applied AGC-2 mechanical load).

In the AGC experiment, significant scope is dedicated to determining the irradiation-induced creep rates of nuclear-grade graphite. Irradiation-induced creep is measured by applying a significant load to half the specimens during irradiation while leaving the other half unloaded. The resulting difference in dimensional change between the loaded and unloaded specimens indicates the amount of irradiation-induced strain on the graphite specimens at a specified temperature and dose range. From this measurement of strain, a creep rate for each graphite type can be calculated as a function of dose at the irradiation temperature. Thus, each capsule is designed to be irradiated at a constant temperature, so only the dose and applied mechanical load are allowed to vary inside each test series capsule. The creep rate of graphite types is therefore measured only as a function of load and dose within each capsule. To ascertain the temperature dependency of irradiation-induced material property changes, such changes measured in similar graphite types under similar dose and load levels must be compared between capsules.

Each test series capsule contains two primary specimen types: creep specimens for providing irradiation creep rate values and mechanical properties, and “piggyback” specimens for providing data on thermal material property changes to the graphite. The creep specimens are 25.4 mm tall by 12.5 mm in diameter and irradiated in the mechanically loaded outer stack positions of the capsule body where an applied load can be imposed upon half the specimens. Piggyback specimens are short (6.3 mm tall by 12.5 mm in diameter) button specimens residing in the axial spine of the capsule receiving no applied load, and they are subjected only to neutron irradiation to assess how a reactor environment affects each specific graphite grade. Together, these two types of specimens provide data on material property changes in stressed and unstressed graphite grades.

The creep specimens are best suited for physical and mechanical testing techniques, such as dimensional change, irradiation creep, elastic modulus, density, and thermal expansion. The piggyback specimens are best suited for thermal and physical testing, such as thermal diffusivity, mass measurements, and density. Because piggyback specimens are not stressed during irradiation, new “experimental” types of graphite and carbon-based materials could be tested for irradiation stability only. These experimental graphite grades are sufficiently stable to be machined into piggyback specimen dimensions, but the carbon-based materials are located in small, hollow graphite cans with dimensions similar to those of the piggyback specimens (either 6.3 or 12 mm tall by 12.5 mm in diameter). These cans are designed to hold specimens of highly oriented pyrolytic graphite (HOPG) and other experimental carbon-based materials of interest to HTR designs. These newer experimental types of carbon-based materials may provide superior irradiation performance and could be used in future reactor designs.

2.2. Description of HDG-1 Test Specimens

As discussed previously, in 2018, the ART graphite program altered the original irradiation plan in order to eliminate the 1,100°C irradiations and re-irradiate the 600 and 800°C specimens under an extended dose range of approximately 1–15 dpa. Specimens previously nominally irradiated at 600°C will be irradiated in HDG-1, while irradiation of specimens at 800°C will be accomplished in HDG-2. To date, the specimens irradiated at 600°C for use in HDG-1 (from the AGC-1 and AGC-2 capsules) have undergone initial irradiation (0.5–7 dpa) and full PIE testing, the specimens irradiated at 800°C (from the AGC-3 and AGC-4 capsules) have undergone initial irradiation (0.5–8.5 dpa), and the AGC-4 specimens are being prepared for PIE in 2021. PIE is already complete for the AGC-3 specimens.

2.2.1. Graphite Specimens

The HDG-1 experiment capsule will contain 576 specimens. These specimens are composed of pre-irradiated specimens from the AGC-2 experiment, repurposed un-irradiated specimens from the AGC-5 experiment, and new specimens specific to the HDG-1 experiment (see Table 1).

Unique to the HDG-1 capsule are new pencil specimens, 0.156 in. in diameter by 0.749 in. long. Special graphite cans were fabricated to contain these new pencil specimens during irradiation, as shown in Figure 3. Each can holds three pencil specimens in the same amount of space required for one creep specimen (0.492 in. in diameter by 1 in. in length). As seen in Table 1, 90 pencil specimens encompassing all the major graphite grades are planned for HDG-1. All together, these 90 specimens will require the same amount of space as only 30 creep specimens, tripling the amount of unstressed irradiation property data that can be gathered using the same volume.

Table 1. Graphite grades and grain orientations within the HDG-1 capsule.

Grade	Specimen Source	Specimen Type	Nominal Dimensions	Grain Orientation	
				WG	AG
2114	AGC-2	Creep	Ø12.5 × 25.4 mm	0	0
NBG-17	AGC-2	Creep	Ø12.5 × 25.4 mm	17	6
NBG-18	AGC-2	Creep	Ø12.5 × 25.4 mm	27	12
IG-110	AGC-2	Creep	Ø12.5 × 25.4 mm	24	1
PCEA	AGC-2	Creep	Ø12.5 × 25.4 mm	30	12
IG-430	AGC-2	Creep	Ø12.5 × 25.4 mm	30	0
2114	AGC-2	Piggyback	Ø12.5 × 6.3 mm	0	17
NBG-17	AGC-2	Piggyback	Ø12.5 × 6.3 mm	6	3
NBG-18	AGC-2	Piggyback	Ø12.5 × 6.3 mm	8	4

Grade	Specimen Source	Specimen Type	Nominal Dimensions	Grain Orientation	
				WG	AG
IG-110	AGC-2	Piggyback	Ø12.5 × 6.3 mm	10	0
PCEA	AGC-2	Piggyback	Ø12.5 × 6.3 mm	7	5
IG-430	AGC-2	Piggyback	Ø12.5 × 6.3 mm	10	0
2114	New	Creep	Ø12.5 × 25.4 mm	15	0
NBG-17	New	Creep	Ø12.5 × 25.4 mm	0	0
NBG-18	New	Creep	Ø12.5 × 25.4 mm	0	0
IG-110	New	Creep	Ø12.5 × 25.4 mm	0	0
PCEA	New	Creep	Ø12.5 × 25.4 mm	0	0
IG-430	New	Creep	Ø12.5 × 25.4 mm	0	0
2114	New	Piggyback	Ø12.5 × 6.3 mm	20	0
NBG-17	New	Piggyback	Ø12.5 × 6.3 mm	19	21
NBG-18	New	Piggyback	Ø12.5 × 6.3 mm	19	19
IG-110	New	Piggyback	Ø12.5 × 6.3 mm	19	21
PCEA	New	Piggyback	Ø12.5 × 6.3 mm	23	18
IG-430	New	Piggyback	Ø12.5 × 6.3 mm	44	0
2114	New	Pencil	Ø3.95 × 19.03 mm	0	3
NBG-17	New	Pencil	Ø3.95 × 19.03 mm	6	12
NBG-18	New	Pencil	Ø3.95 × 19.03 mm	6	9
IG-110	New	Pencil	Ø3.95 × 19.03 mm	9	9
PCEA	New	Pencil	Ø3.95 × 19.03 mm	6	12
IG-430	New	Pencil	Ø3.95 × 19.03 mm	18	0

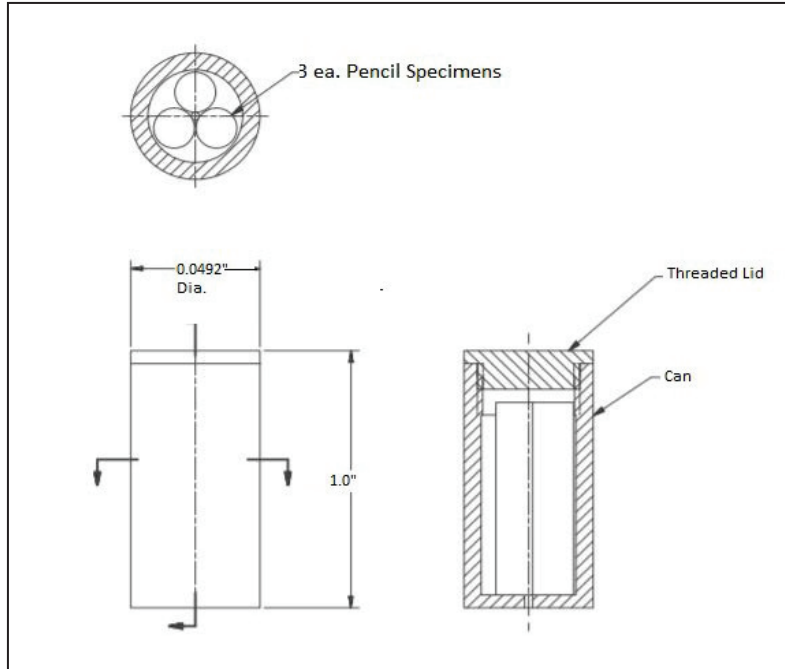


Figure 3. HDG-1 pencil specimen can, ref. DWG-605048.

Work instructions ART/AGC-WI-001, “HDG-1 Specimen Fabrication,” Rev. 2-7-19⁴ and ART/AGC=WI=002, “HDG-1 HOPG and Pencil Can Fabrication and Loading,” Rev. 4-25-19⁵ describe in detail the fabrication of additional IG-430 buttons, pencil specimens, and pencil specimen containers. Each pencil can and specimen is laser-engraved with a unique identification number that makes each pencil specimen loaded into each pencil can traceable (see Table 2).

Each pencil specimen has had coefficient of thermal expansion (CTE), Young’s modulus, electrical resistivity, dimensional, and mass pre-irradiation measurements performed on it. It should be noted that completed studies documented in INL notebooks (LAB-1318, LAB-1320 and LAB 2562) show that this pencil geometry will produce physical and thermal property values with similar means and variances as the full-sized creep specimens.

Table 2. Pencil can numbering and loading.

Pencil Can Number	Pencil Specimen 1	Pencil Specimen 2	Pencil Specimen 3	Graphite Grade
PCAN 1	AP-1P	AP-2P	AP-3P	NBG-17
PCAN 2	BW-1P	BW-2P	BW-3P	NBG-18
PCAN 3	FW-1P	FW-2P	FW-3P	IG-430
PCAN 4	BP-1P	BP-2P	BP-3P	NBG-18
PCAN 5	AP-4P	AP-5P	AP-6P	NBG-17
PCAN 6	BP-4P	BP-5P	BP-6P	NBG-18
PCAN 7	DA-1P	DA-2P	DA-3P	PCEA
PCAN 8	EW-1P	EW-2P	EW-3P	IG-110
PCAN 9	AP-7P	AP-8P	AP-9P	NBG-17
PCAN 10	EW-4P	EW-5P	EW-6P	IG-110
PCAN 11	DA-4P	DA-5P	DA-6P	PCEA

Pencil Can Number	Pencil Specimen 1	Pencil Specimen 2	Pencil Specimen 3	Graphite Grade
PCAN 12	EA-1P	EA-2P	EA-3P	IG-110
PCAN 13	DA-7P	DA-8P	DA-9P	PCEA
PCAN 14	FW-4P	FW-5P	FW-6P	IG-430
PCAN 15	DW-1P	DW-2P	DW-3P	PCEA
PCAN 16	BW-4P	BW-5P	BW-6P	NBG-18
PCAN 17	BP-7P	BP-8P	BP-9P	NBG-18
PCAN 18	DA-10P	DA-11P	DA-12P	PCEA
PCAN 19	FW-7P	FW-8P	FW-9P	IG-430
PCAN 20	TA-1P	TA-2P	TA-3P	2114
PCAN 21	DW-4P	DW-5P	DW-6P	PCEA
PCAN 22	AW-1P	AW-2P	AW-3P	NBG-17
PCAN 23	AW-4P	AW-5P	AW-6P	NBG-17
PCAN 24	AP-10P	AP-11P	AP-12P	NBG-17
PCAN 25	EA-4P	EA-5P	EA-6P	IG-110
PCAN 26	FW-10P	FW-11P	FW-12P	IG-430
PCAN 27	EA-7P	EA-8P	EA-9P	IG-110
PCAN 28	EW-7P	EW-8P	EW-9P	IG-110
PCAN 29	FW-13P	FW-14P	FW-15P	IG-430
PCAN 30	FW-16P	FW-17P	FW-18P	IG-430

2.2.2. Flux Wires

Over the past few years, considerable improvements to AGC flux wire analysis were implemented. Flux wires are a critical step in calculating the total received neutron dose within all AGC/HDG irradiation capsules. To improve both the accuracy and repeatability of the AGC dose calculations, significant effort was leveraged to improve the Monte Carlo N-Particle calculations, increase the resolution of flux wire activity by increasing the number of flux wires within the irradiation capsule, and employ more accurate flux wire activation measurements.⁶ HDG-1 is the first irradiation capsule to begin using these improvements, including the larger flux wire variety.

HDG-1 flux wires were fabricated at INL as per Work Instruction ART/AGC-WI-004, "HDG-1 Flux Wire V-Can Fabrication and Assembly," Rev. 12-5-19⁷. The new flux wire assembly consists of seven different flux wire materials (making the full spectrum of irradiation detectable), rather than the mere three materials used previously. Each flux wire is encapsulated in a 99.8% by weight, pure vanadium can. These vanadium cans are then placed into a graphite holder the outside dimensions of which equal two piggyback specimens (12.5 mm in diameter by 12.5 mm in length). An additional (empty) vanadium can is placed inside the graphite flux wire assembly for use in background subtraction when gamma spectrometry is performed on each vanadium can containing one of the flux wire materials. Twelve of these graphite flux wire assemblies are evenly distributed in the center channel of the HDG-1 capsule.

This differs from the flux wire locations in previous AGC capsules, where flux wires were located within the outer stacks. All vanadium cans are laser-engraved with identification numbers that correspond to the wire type they contain, and each graphite assembly is laser-engraved with a unique identification number so its vertical position can be identified in the loading order, thus indicating its position relative to the reactor flux (see Table 3).

Table 3. Flux wire vanadium can loading for each graphite can holder.

Graphite Can Holder No.	XW-1	XW-2	XW-3	XW-4
Flux Wire Number	A01	A02	A03	A04
	B01	B02	B03	B04
	C01	C02	C03	C04
	T01	T02	T03	T04
	F01	F02	F03	F04
	N01	N02	N03	N04
	E01	E02	E03	E04
	X01	X02	X03	X04
Graphite Can Holder No.	XW-5	XW-6	XW-7	XW-8
Flux Wire Number	A05	A06	A07	A08
	B05	B06	B07	B08
	C05	C06	C07	C08
	T05	T06	T07	T08
	F05	F06	F07	F08
	N05	N06	N07	N08
	E05	E06	E07	E08
	X05	X06	X07	X08
Graphite Can Holder No.	XW-9	XW-10	XW-11	XW-12
Flux Wire Number	A09	A10	A11	A12
	B09	B10	B11	B12
	C09	C10	C11	C12
	T09	T10	T11	T12
	F09	F10	F11	F12
	N09	N10	N11	N12
	E09	E10	E11	E12
	X09	X10	X11	X12

2.2.3. HOPG Specimens

HOPG specimens were loaded into graphite containers as per ART/AGC-WI-002, “HDG-1 HOPG and Pencil Can Fabrication and Loading,” Rev. 4-25-19. These specimens consisted of:

- 1 ea./container: SPI Supplies HOPG SPI-1 Grade #476HP, 5 × 5 × 1 mm, Lot #:1131201
- 3 ea./container SPI Supplies HOPG SPI-1 Grade #425HP-MB, 3-mm Disk, Lot #: 1200528.

Dimensions of the larger HOPG specimens are listed in Table 4. These HOPG cans are located in the center channel of the experiment capsule.

Table 4. HOPG specimen dimensions.

HOPG Can Number	3-mm Disk HOPG Spec.	5 × 5 x 1 mm HOPG Spec.	Dimension 1 (mm)	Dimension 2 (mm)	Dimension 3 (mm)
HOPG1	3 ea.	1 ea.	5.137	5.131	1.252
HOPG2	3 ea.	1 ea.	5.212	5.304	0.800
HOPG3	3 ea.	1 ea.	5.190	5.181	0.790
HOPG4	3 ea.	1 ea.	5.001	5.041	1.362

NOTE: Refer to ART/AGC-WI-002, “HOPG and Pencil Can Fabrication and Loading,” Rev. 4-25-19 for details on dimension location and orientation.

2.2.4. Arrangement and Shipping of HDG-1 Specimen Stacks

All specimens were ordered and arranged prior to insertion into the HDG-1 capsule. These specimens consisted of both pre-irradiated AGC-2 and unirradiated AGC-5 specimens, 30 new pencil specimen cans containing 90 pencil specimens, 4 ea. of HOPG cans, and 12 ea. of flux wire cans. A total of 576 individual specimens held in barcoded snap-cap containers were first gathered and staged in compartmentalized boxes corresponding to each upper or lower section of the seven capsule stacks.

Following NQA-1-compliant ART-AGC Work Instruction No. ART/AGC-WI-005⁸, barcoded specimen numbers were verified, pictures were taken to document initial conditions, and the specimens were stacked into a tray to be slid into individual polycarbonate tubes. Each tube contained the specimens associated with one of the seven channels in either the upper or lower stacks—for a total of 14 tubes.

These tubes were sealed, bagged, and loaded into a lead-lined barrel for shipment from INL’s Research Center to the ATR Test Train Assembly Facility for assembly into the HDG-1 capsule. Once inside the assembly facility, the polycarbonate tubes were aligned with the capsule specimen holder, enabling the full group of verified specimens to be efficiently slid into the correct stack position inside the HDG-1 capsule.

2.2.5. Expected Dose

Due to limited capsule volume and the large number of graphite grades being investigated, the stacking order must ensure the equal distribution of specimens over the entire dose range in the irradiation capsule. For six graphite grades, three different mechanical load levels, and specimens that were 25.4 mm long, careful planning was required to evenly distribute as many specimens as possible over the entire dose range. For this study, some graphite grades were allowed more specimens than other types. This slightly skewed the number of specimens from grade to grade. To further complicate the stacking order, the graphite specimens’ microstructural orientation to the applied load during irradiation must also be considered because with-grain creep rates are expected to differ from against-grain creep rates for dose levels larger than the turnaround dose.

The final loading configuration of all the stacks was established once a smooth dose profile was achieved for each graphite type (Appendix C, Table C-1). Plots of calculated dose vs. specimen across the total accumulated dose range were made for each graphite grade to ensure a smooth dose profile. It should be noted that the AGC-2 dose data were added to these plots. These plots were used to identify any gaps in the dose curves for each graphite grade. Figure 3 shows example dose vs. specimen plots for both loaded and unloaded graphite Grade 2114. Dose plots for the other graphite grades can be found in Figure D-1–Figure D-10 in Appendix D.

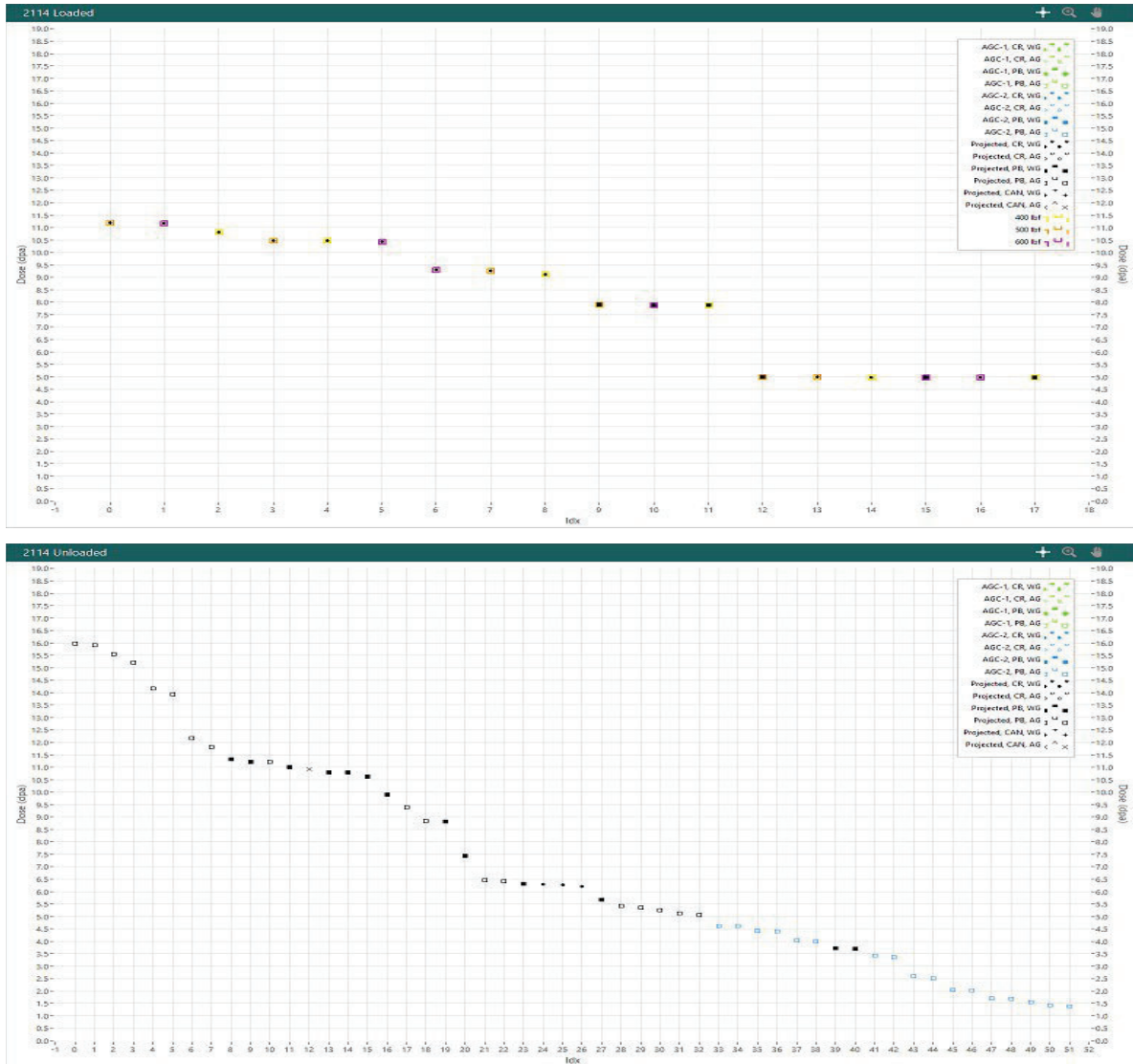


Figure 4. Estimated dose profiles for loaded and unloaded 2114 specimens.

3. MATERIAL PROPERTY MEASUREMENTS

A summary of the material testing performed on all specimens is shown in Table 5. All testing was performed to American Society for Testing and Materials (ASTM) approved standards. Thermal diffusivity, CTE, electrical resistivity, elastic modulus, mass, and dimensional measurements were performed to characterize the unirradiated AGC-5, the irradiated AGC-2, the new HDG-1 pencil specimens, and the piggyback specimens. Details of the testing standards used and any variances necessary due to the small specimen size—along with equipment calibration, personnel training on the testing methodology, and data acquisition—are specified in two specimen characterization plans: PLN-4657, “AGC-2 Graphite Specimen Post-irradiation Characterization Plan,” Rev. 0 and “AGC-5 Graphite Specimen Pre-Irradiation Characterization Plan,” Rev. 0, Table 5, property measurement standards.

Table 5. Graphite testing standards.

Measurement	ASTM Standard	Material Property
Standard Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles	ASTM C559-16	Bulk density
Standard Test Method for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance	ASTM C747-16	Young’s modulus (flexural mode)
Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining an Approximate Young’s Modulus	ASTM C769-98(2005)	Young’s and shear modulus
Standard Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature	ASTM C611-98(2016)	Electrical resistivity
Standard Test Method for Thermal Diffusivity by the Flash Method	ASTM E1461-13	Thermal diffusivity
Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Dilatometer	ASTM E228-17	Coefficient of thermal expansion

NOTE: *All ASTM standards are reapproved every 5 years. During this review, the technical content of the standard was confirmed to still be valid. In some cases, this process of reapproval will give rise to a more in-depth revision. Whenever a new revision is released, the publication year is changed. Over the long duration of the full ART AGC irradiation experiment matrix, the ASTM standards followed will be reapproved and revised. These standards are reviewed for technical equivalency prior to each publication of an AGC capsule characterization plan. This makes it possible to compare and analyze data across the full experiment matrix. When a revision is technically equivalent to its predecessor, the new version is used and referenced throughout the full test (e.g., characterization plan, pre-irradiation analysis, and post-irradiation analysis). If the revision is not technically equivalent, the previous version will continue to be followed and referenced.*

3.1. Calibration and Functional Validation

The measurement protocol consists of calibration, functional validation, and data acquisition. Functional validations established for each measurement in collaboration with the instrument manufacturer are performed periodically to ensure accurate, consistent data. All validations are performed on traceable standards and then documented in retrievable laboratory notebooks associated with each measurement. In the event of instrument functional-validation failure, the reason for the failure is investigated and resolved prior to that measurement's being used for further characterization. Once such resolution occurs, a determination is made as to the failure's impact on data captured prior to the failure, going all the way back to the last valid measurement. If data captured during this interval are deemed suspect, the impacted data will be evaluated for accuracy and a decision made as to whether to repeat the measurement.

LWP-13455, "Control of Measuring and Test Equipment,"¹¹ is followed for calibration standards, methods, and frequencies established for each measurement. Where it is not possible to use the INL Standards and Calibration Laboratory, calibration by user procedures is established based on ASTM standards and test equipment manufacturer's instructions, performed against international standards. These procedures are documented in laboratory notebooks associated with each measurement.

3.2. Mass, Dimensions, and Bulk Density

Dimensional change is a key parameter affecting the performance of graphite in a neutron environment. Determining volumetric and linear dimensions as a function of temperature and neutron dose is necessary for understanding critical performance measures such as dimensional change turnaround, irradiation creep, and irradiation-induced internal stresses imposed on graphite components. Dimensional and mass measurements are performed to ASTM Standard C559-16¹², which describes in detail the procedure for making dimensional measurements and calculating bulk density.

The manufacturer's accuracy of the dial micrometers is said to be 2 μm . This correlates to a 0.008% accuracy for a 25.4-mm measurement. However, when evaluating the uncertainty of the density determination, other factors must be considered, such as the hardness of the material, the force with which the micrometer blade is engaged with the material, specimen temperature variation, technician skill, etc. These and other factors were considered in a propagation-of-error analysis to arrive at an uncertainty of 0.08%, with the measurement of the diameter most contributing to the error.

3.3. Electrical Resistivity

Electrical resistivity is a rapid, simple means of determining the grain orientation, structure, and crystallinity of graphite. In conjunction with optical microscopy, it can be used to determine the microstructural texture of graphite components with a minimum of specimen preparation work.

Resistivity is measured as per ASTM C611-98 (2016), "Standard Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature."¹³ The measurement technique is commonly referred to as a 4-point probe. It consists of passing a known current through the specimen and measuring the voltage across the specimen at known locations.

Based on Ohms Law, the resistance is measured and the resistivity is calculated from:

$$r = R \times A / L$$

where:

R = measured resistance

A = cross-sectional area

L = the length over which the voltage is measured.

Figure 5 shows a test fixture designed and fabricated at INL that allows a cylindrical specimen to be rotated for multiple measurements of voltage on its circumference while current is flowing through it.

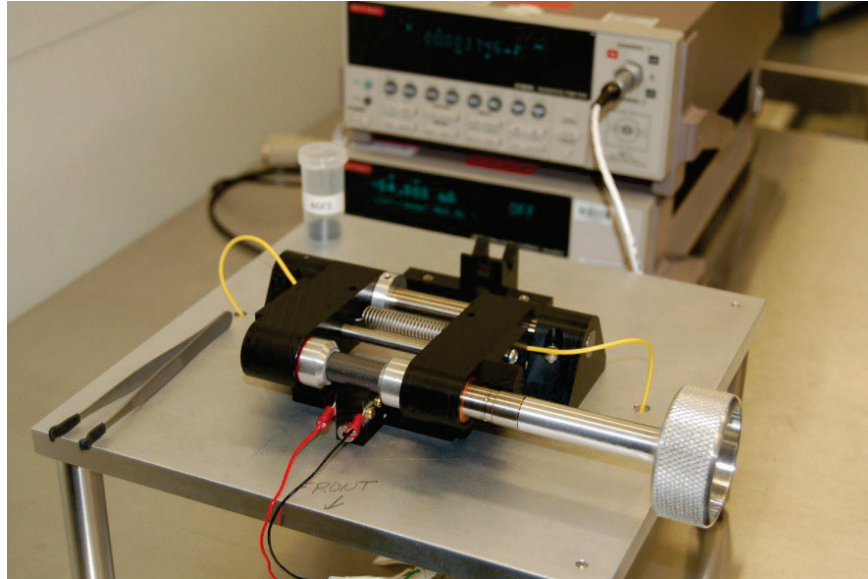


Figure 5. Electrical resistivity measurement station.

Uncertainty in the resistivity measurement is mainly due to the contact resistance between the specimen and the contacting blades for the voltage measurement. Specimen temperature and the temperature of other bimetal junctions in the voltage-measuring leads are also factors. These effects are minimized by passing the current through the specimen in two directions and averaging the measured voltage for each direction. In this way, any thermoelectric or small differences in junction resistance will cancel. A round robin test series reported in ASTM C611-98 precision and bias section states a lab-to-lab variability of 2.5%. A round robin test series such as this would take into account the variables discussed above and is considered a good estimate of the measurement uncertainty.

3.4. Approximation of Elastic Modulus from the Measurement of Sonic Velocity

It is necessary to understand the mechanical properties of graphite in order to determine the structural integrity of graphite components. These properties are essential to determining the structural strength and integrity of the reactor core. The as-received and irradiated values are needed for whole-core models that will be used for the graphite design code. This elastic modulus test is carried out in accordance with ASTM C769-98 (2005), “Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining an Approximate Value of Young’s Modulus.”¹⁴ In this measurement, the transmitting piezoelectric transducer sends a 2.25-MHz soundwave through the specimen. At the opposite end of the specimen, the acoustic wave is received by another piezoelectric transducer. The sonic velocity of the specimen is the ratio of specimen length to the signal time lapse between transducers.

An approximate value for Young’s modulus, E , can be obtained from:

$$E = \rho V^2$$

where:

ρ = specimen density

V = sonic velocity.

Figure 6 shows the sonic velocity measurement station used for AGC and HDG specimens. In the foreground are the fixtures for clamping the specimen between the transducer and receiver. These fixtures were specifically designed and fabricated at INL for this application. They have unique features that improve measurement accuracy, precision, and efficiency. For example, measurement precision is improved because the spring-loaded clamp applies consistent pressure between the transducers and specimen, resulting in repeatable couplant thickness. The specimens are easily and rapidly loaded into the fixture using the cam-operated clamp.

As specified in Paragraphs 8.1 and 8.5.1 of ASTM C769-98 (2005), a suitable coupling medium should be used and reported along with the data. Here, Shear Gel manufactured by Sonotech, Inc., is used for a shear wave couplant and Ultrigel II, also manufactured by Sonotech, Inc., is used for the transverse wave couplant.

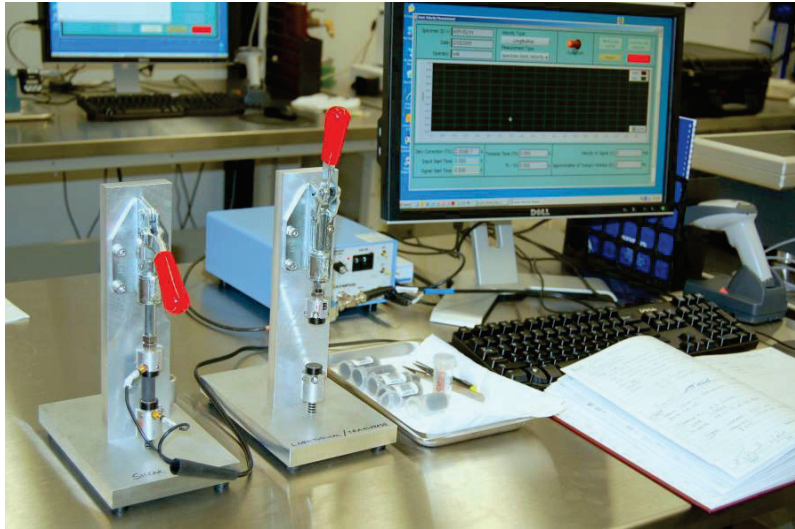
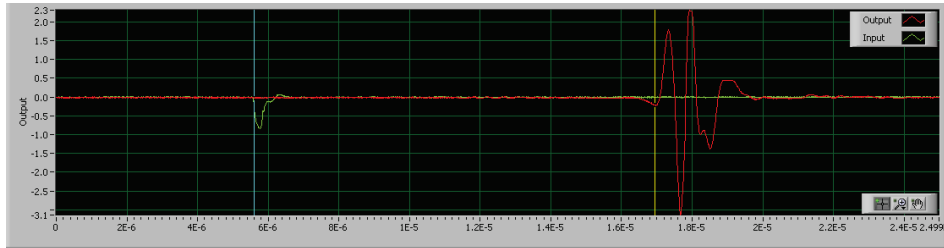


Figure 6. Sonic velocity measurement station.

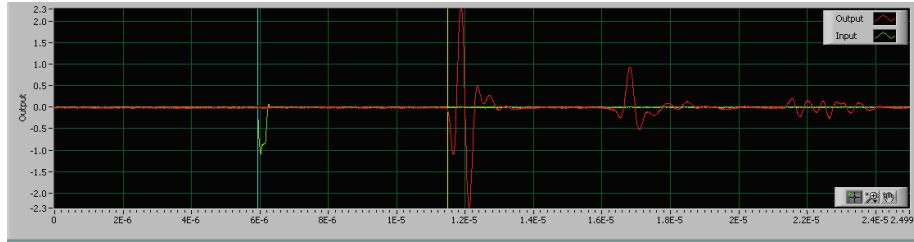
Figure 7 shows the LabVIEW software's user interface display for sonic velocity measurements after scanning the barcode of the specimen to be tested. This screen is used to acquire sonic velocity measurements of a specimen in both the longitudinal and shear directions. Operating much like an oscilloscope, the cursors automatically mark the time between the transmitted wave and the received wave. Also shown in Figure 7 are two examples of the shear wave and transverse wave timing locations for properly coupled specimens. The specimen length divided by this transit time equals the sonic velocity.

The uncertainty in determining elastic moduli from the measurement of sonic velocity comes from several sources. First there is the effect of material- and geometry-related dispersion of the transmitted wave. ASTM C769-98 (2005) provides guidance on minimizing this problem by helping to select the correct frequency. This technique also assumes linear elastic behavior, despite graphite not being a completely linearly elastic material. And finally, operator judgment as to the placement of the timing cursors is somewhat subjective. Clean wave forms on which to base such judgments highly depend on the quality of the transducer-material coupling.

These sources of error are difficult to quantify; therefore, they are difficult to combine in a propagation-of-error analysis. However, ASTM C769-98 (2005) describes in some detail a round robin test series between different laboratories. Using round robin test data to determine a coefficient of variation (COV) provides a good means of estimating the measurement uncertainty. With caution, the COV of 3.8% reported in ASTM C769-98 (2005) is taken here to be representative of the uncertainty of these measurements. When considering a single material and making comparisons between the pre- and post-irradiation values, the precision of these measurements is good enough to consider differences greater than 4% significant. However, one is cautioned to refrain from using the values here as absolute, or better than $\pm 10\%$ accurate.



Shear wave timing



Transverse wave timing

Sonic Velocity Measurements

Specimen ID #: <input type="text"/>	Velocity Type: <input type="button" value="Longitudinal"/>	 Pulsar OFF	<input type="button" value="Write Data to File"/>	<input type="button" value="Continue with next test"/>
Date: <input type="text" value="1/29/2009"/>	Measurement Type: <input type="button" value="Specimen Sonic Velocity"/>	<input type="button" value="Reset"/>	<input type="button" value="Finished"/>	
Operator: <input type="text"/>				

Zero Correction (T0): <input type="text" value="0.000"/> s	Traversal Time (Tt): <input type="text" value="1.110E-5"/> s	Velocity of Signal (v): <input type="text" value="0"/> m/s
Input Start Time: <input type="text" value="2.480E-5"/> s	Tt - T0: <input type="text" value="1.110E-5"/> s	Approximation of Young's Modulus (E): <input type="text" value="0"/> Pa
Signal Start Time: <input type="text" value="3.590E-5"/> s		

Figure 7. Sonic velocity measurement user interface.

3.5. Modulus of Elasticity by Measurement of Fundamental Frequency

As previously discussed, the mechanical properties of graphite must be understood in order to determine the structural integrity of the reactor core structure by assessing the strength and integrity of the graphitic components. This test method measures the fundamental resonant frequency of test specimens of suitable geometry by exciting them mechanically with a singular elastic strike. Specimen supports, impulse locations, and signal pick-up points are selected to induce and measure specific modes of the specimen's transient vibration. The transient signals are analyzed, and the fundamental resonant frequency is isolated and measured by the signal analyzer. The measured fundamental resonant frequency, specimen dimensions, and mass are used to calculate the dynamic Young's modulus, shear modulus, and Poisson's ratio per ASTM C747-16, "Standard Test Method for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance."¹⁵ The fundamental frequency measurement station is shown in Figure 8.



Figure 8. Fundamental frequency measurement station.

After placing a specimen in the test fixture, the user excites it by lightly tapping it with a small mechanical impulse. The specimen is supported in such a way that it vibrates at its natural frequency. A microphone placed underneath one end of the specimen, in combination with the GrindoSonic frequency-processing electronics, measures this frequency, which is recorded and displayed by the computer. The modulus of elasticity is calculated and displayed next to the newly acquired frequency. If the results are satisfactory, the user can press the "Save 1st Frequency" button and move on to the next measurement. In accordance with the recommendations of ASTM C747-16, ten readings of the fundamental frequency are measured and averaged prior to recording the test results.

ASTM C747-16 describes in detail a round robin test series using graphite materials, along with an analysis of the propagation of errors in the calculation of moduli from the measurement of resonant frequency, geometry, and mass of the specimen. This error analysis reveals that the major sources of experimental variation are the fundamental frequency measurement and the smallest dimension (diameter) of the specimens (due to their higher exponent in the modulus calculations). Both the propagation of error analysis and the round robin data indicated an uncertainty of less than 2% for this test method. However, the creep specimens tested here do not meet the geometry requirements of ASTM C747-16. With a length-to-diameter ratio of only 2, these specimens are, at times, difficult to excite consistently and in a single mode of vibration. Once a resonant frequency was determined by an experienced operator for the flexural mode of vibration, it was easily repeated within 2% uncertainty.

3.6. Thermal Expansion

Understanding the thermal expansion behavior of graphite components, represented as the CTE, is critical for determining dimensional changes resulting from changing temperatures and temperature gradients. Localized internal and external stresses can be imposed on graphite core components as they experience differential thermal expansion. The irradiation dimensional change response is also affected by the thermal expansion, with grades exhibiting higher CTE that have lower turnaround neutron dose levels. Finally, the thermal expansion is highly dependent upon the graphite microstructure, such as orientation/anisotropy, pore size and distribution, and crystallinity. Determining the extent of the CTE change as a function of irradiation dose and temperature will be a key parameter for reliable calculation of stress states within graphite components, volumetric changes, and irradiation creep rates.

CTE is measured according to ASTM standard E228-17.¹⁶ This test method uses a push-rod-type dilatometer to determine the change in length of a graphite specimen relative to that of the specimen holder as a function of temperature. The temperature is varied over the desired range at a slow constant heating or cooling rate. The mean coefficient of thermal expansion, α , is calculated from the measured data as follows:

$$\alpha = \frac{1}{L_0} \frac{\Delta L}{\Delta T}$$

where:

L_0 = specimen's initial length

ΔL = change in length

ΔT = temperature difference between a specified reference temperature and the temperature at which the change in length was measured.

A Netzsch DIL 402 C commercial system (Figure 9) currently used at INL does not have the capability to cool the specimen below ambient temperature. Therefore, the specimen's initial length at 20°C is linearly extrapolated from expansion data between 100 and 150°C, and the mean CTE is calculated using a 20°C reference temperature.

The greatest source of experimental error in the dilatometry test method described here is the correction made for the expansion of the specimen holder and push-rod/linear variable differential transformer mechanism. This differential between the specimen and the apparatus must be considered to isolate only the specimen expansion. Studies reported in the precision and bias section of ASTM E228-17 indicate that this type of dilatometry can achieve up to 4% accuracy when calibrations are performed carefully.

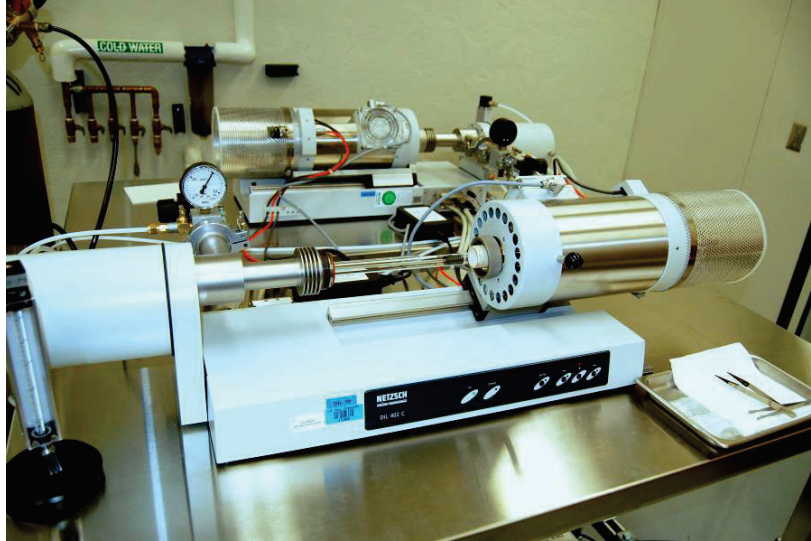


Figure 9. Commercial push-rod dilatometer for measuring CTE.

3.7. Thermal Diffusivity

The ability to conduct heat through the graphite core is critical to the operational efficiency of the HTR and for passive removal of decay heat during cooldown. Reduction of thermal conductivity within graphite can have a significant effect on the passive heat removal rate and, thus, the peak temperature that the core and, subsequently, the fuel particles will experience during off-normal events. Determining changes to this conductivity as a function of irradiation dose and temperature is important for the safety analysis. Here, ASTM E1461-13¹⁷ is followed for calculating thermal diffusivity and conductivity. Thermal diffusivity (δ) is measured and defined as the ratio of thermal conductivity to volumetric heat capacity:

$$\delta = \frac{k}{\rho C_p}$$

where:

k = thermal conductivity

ρ = density

C_p = specific heat.

Diffusivity measurements are performed on the button-shaped piggyback specimens. A pulsed laser is used to subject one surface of the specimen to a high-intensity, short-duration energy pulse. The energy of this pulse is absorbed on the front surface of the specimen, and the resulting rise in rear-face temperature is recorded. The thermal diffusivity is calculated from the specimen thickness and the time required for the rear-face temperature to reach 50% of its maximum value. A commercially available laser flash apparatus (LFA), complete with vendor-developed software for instrument control and data acquisition, is used (see Figure 10).

Uncertainty in the measurement of thermal diffusivity arises from specimen heat loss and temperature measurement. Specimen temperature measurement is performed with a calibrated Type-S thermocouple in the near-vicinity of the specimen. Relatively straightforward, this measurement is typically only a small contributor to the overall measurement error or uncertainty.

The primary contributor to the measurement uncertainty is heat loss from the specimen. Because this measurement technique depends on the assumption of one-dimensional heat transfer from the flat face receiving the laser pulse to the flat face radiating to the detector, heat loss errors are mainly attributed to radiative heat loss from the circumference of the specimen at temperatures above 300°C. Several correction models are typically provided with the instrument software to account for this heat loss. As the specimen diameter-to-thickness ratio decreases, the heat loss increases to the point that the correction models can no longer account for the error. A study was performed on the limitations of the models made available with the NETZSCH LFA, and the dependence of the diameter-to-thickness ratio on measurement error. In this study, the heat loss models were applied to data on specimens with various diameter-to-thickness ratios, at specimen temperatures between 25 and 1,000°C. It was determined that the Cowan model, along with diameter-to-thickness ratios greater than or equal to two, resulted in determination of the diffusivity within the ASTM E1461-13- and the manufactures specified uncertainties of 4 and 3%, respectively.¹⁸ This was further verified by instrument functional tests performed monthly on a pure-iron validation specimen the diffusivity of which was determined to be within 3% of the Touloukian values between 100 and 700°C.¹⁹



Figure 10. LFA measurement station for determining thermal diffusivity.

4. DATA ANALYSIS

Data gathered for the characterization of HDG-1 specimens are contained in the appendices of this report. These appendices contain only specimen measurements that have not been reported in other reports—namely, all of the pencil specimens and the newly machined IG-430 piggyback specimens. Appendix A contains plots of the individual datapoints for each specimen. The dashed lines in each plot give the upper and lower limits of the interquartile range (IQR). These limits are established by the lesser of 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 quartiles. Any data value outside these limits is a suspected outlier of the established pattern. However, it is important to note that these outlying values are subject not only to measurement variability, but also material variability; therefore, the values cannot necessarily be discarded. These outlying values are examined in the context of the entire dataset and will be further evaluated post-irradiation. Other statistical parameters are calculated and presented in the tables of Appendix B. The mean, standard deviation, and COV are all calculated for the different measurement datasets and graphite types. Upper and lower limits are presented in the tables of Appendix B, with the IQR limits described above.

There are many ways to combine and compare the data presented here. In doing so, the validity of the data is exercised and scrutinized. First, the datasets are considered independently via the statistical analysis described above. Additionally, a limited comparison of absolute property values is performed between different graphite types and grades. The degree of isotropy is also evaluated for a limited number of grades by calculating the anisotropy ratio:

$$\text{Anisotropy Ratio} = \frac{\text{Value of the Property in the Against-Grain Direction}}{\text{Value of the Property in the With-Grain Direction}}$$

Note that, in the case of isostatically molded graphite, with-grain and against-grain indicate specimens taken from orthogonal planes in the billet.

4.1. Mass, Dimensions, and Density Data Analysis

Plots of the measured mass, dimensions, and density for all the pencil specimens and new piggyback specimens used in HDG-1 are shown in Figure A-1–Figure A-28 (Appendix A). These plots also show the measurement’s IQR limits. For plots of previously irradiated specimens and pre-irradiated specimens to have been used in AGC-5, refer to INL/EXT-15-36244, “AGC-2 Specimen Post-Irradiation Data Package Report,” and INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report,” respectively.

One of the most important parameters in the AGC experiment is the dimensional change of the specimens due to irradiation and stress. Therefore, particular care must be taken in evaluating the dimensional measurements. The scatter in the pencil specimens’ dimensional data is reasonable, with the length measurements having a COV of 0.09% or less and the diameter measurements having a COV of 0.22% or less (Table B-1 and Table B-2). This is a function of both machining consistency and measurement precision. However, the length or diameter measurements for eight specimens from among the various grades fall outside their respective IQRs. This does not necessarily indicate a measurement error. It is possible that the specimen dimensions are simply different than the majority. Some material variability is also possible among the specimens. Those specimens with dimensional values outside the IQR are listed in Table 6 and will be closely evaluated post-irradiation.

Table 6. Creep specimen length outliers.

Grade	Specimen ID	Specimen Type	Measurement
IG-430	FW2101	Piggyback	Diameter
IG-430	FW2141	Piggyback	Diameter
IG-430	FW2142	Piggyback	Diameter
IG-430	FW2148	Piggyback	Diameter
IG-430	FW2104	Piggyback	Length
IG-430	FW2142	Piggyback	Length
NBG-17	BW2P	Pencil	Length
IG-430	FW15P	Pencil	Length

4.2. Electrical Resistivity

Plots of electrical resistivity for all pencil specimens used in HDG-1 are shown in Figure A-35–Figure A-40 for graphite grades 2114, IG-110, IG-430, NBG-17, NBG-18, and PCEA. Resistivity measurements were performed on the creep and pencil specimens only. Plots of specimen resistivity previously measured for AGC-2 post-irradiation or AGC-5 pre-irradiation can be found in INL/EXT-15-36244, “AGC-2 Specimen Post-Irradiation Data Package Report,” and INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report,” respectively.

COVs for the combined orientation specimens vary according to grade. IG-430 had the lowest at 1.28%, and IG-110 had the highest at 4.36% (Table B-7). After performing IQR analysis for each grade, only two specimens had resistivity values outside the IQR limits. NBG-18 had two against-grain specimens larger than the upper IQR limit. Voltage and resistance values for these two specimens were scrutinized and found acceptable in comparison with the other specimens of the same grade. It was decided that these data be kept, as material variability is likely why these specimens exceeded the IQR limits.

In Figure 11 the mean resistivity values for several grades of graphite are plotted for both specimen grain orientations. The anisotropy ratio is displayed above each mean value. NBG-17 exhibited the best isotropy ratio, while PCEA had the largest resistivity difference between the two grain orientations.

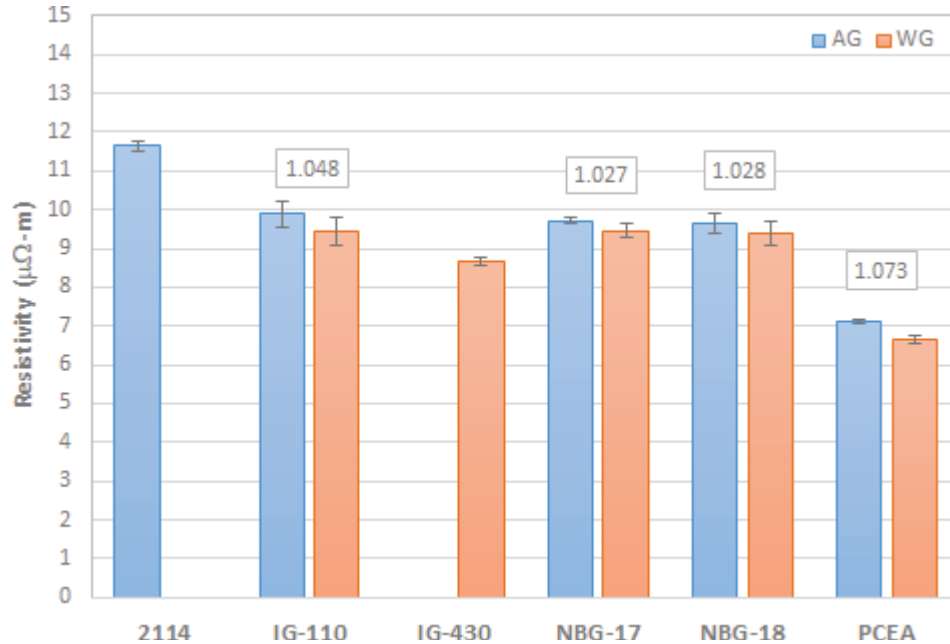


Figure 11. Electrical resistivity of pencil specimens of the major graphite grades. The anisotropy ratio is above each set of data bars. The error bars represent ± 1 standard deviation. Grades 2114 and IG-430 only have one grain orientation.

4.3. Approximation of Elastic Modulus from the Measurement of Sonic Velocity

Figure A-41 shows plots of Young’s and shear modulus that were calculated from the measurement of sonic velocity through the graphite specimens. The only new sonic velocity measurements made for HDG-1 were on the newly machined IG-430 piggyback specimens. Plots of modulus for specimens previously measured for AGC-2 post-irradiation or AGC-5 pre-irradiation can be found in INL/EXT-15-36244, “AGC-2 Specimen Post-Irradiation Data Package Report,” and INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report,” respectively.

Figure 12 shows the relationship between Young’s modulus (measured using the sonic-velocity technique) and the density of IG-430. In general, as the density of the specimen increases, so does the modulus of elasticity.

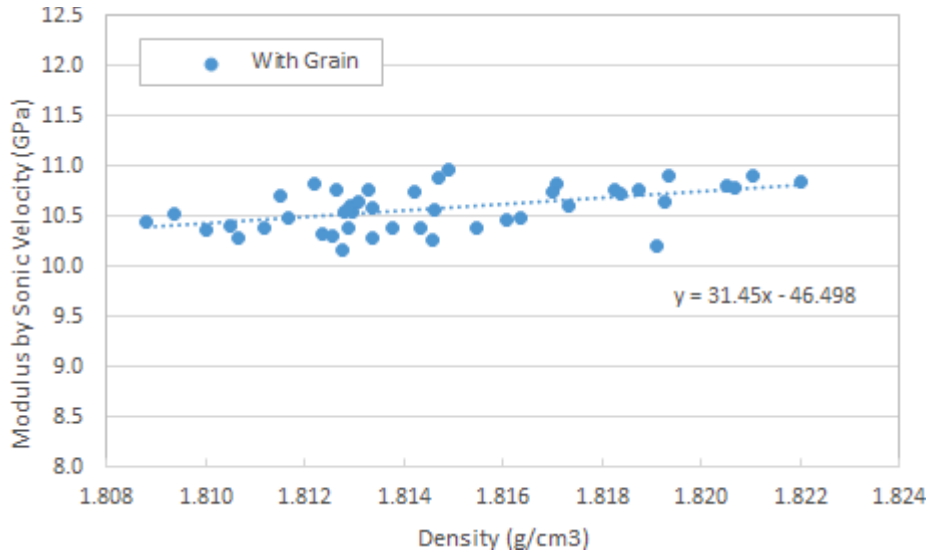


Figure 12. Young’s modulus using the sonic velocity technique vs. density for IG-430.

Young’s and shear moduli statistics are shown for IG-430 in Table B-8. The IQR analysis showed that all the data were within the upper and lower IQR limits. The COVs for Young’s modulus and shear modulus of IG-430 (2% and 1.9%, respectively) were in agreement with the value reported in the ASTM C769 precision and bias section.

Prior AGC specimen testing was performed according to the previous ASTM sonic velocity standard, ASTM-769-98 (2005), which does not use the Poisson factor to calculate the modulus values. To avoid confusion when comparing HDG-1 data to previous AGC data, it was decided to continue to use ASTM-769-98 (2005) and, when necessary, apply the correction. Using the same ASTM test-method version ensures that the unirradiated and irradiated measurements will be consistent, comparable, and without testing-method bias.

4.4. Modulus of Elasticity by Measurement of Fundamental Frequency

Young’s modulus of each pencil specimen was also calculated using the fundamental frequency technique. Plots of modulus by fundamental frequency for specimens previously measured for AGC-2 post-irradiation or AGC-5 pre-irradiation can be found in INL/EXT-15-36244, “AGC-2 Specimen Post-Irradiation Data Package Report,” and INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report,” respectively.

The fundamental frequency modulus results are plotted in Figure A-29–Figure A-34, and the statistical data are contained in Table B-6. Statistically, these data are well-behaved, with the IQR analysis showing three IG-430 measurements, one NBG-17 (against-grain) measurement, and one NBG-18 (against-grain) measurement all as outliers.

Figure 13 shows a comparison of Young’s modulus as calculated from the measurement of fundamental frequency for the primary grades of graphite by grain orientation. None of the graphite grades show an anisotropy ratio higher than 0.98 (NBG-18). PCEA has the largest discrepancy between grain orientations. Its anisotropy ratio was 0.94. The COVs of the mixed grain orientation statistics shown in Table B-8 range from 1.5–6.0%. This is a relatively large range compared to the 1.0–3.8% range from the AGC-5 pre-irradiation report (INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report”), which used the same grades of graphite but excluded IG-430. The small diameters of the pencil specimens may be the reason for this discrepancy because they proved more difficult in generating consistent frequency readings.

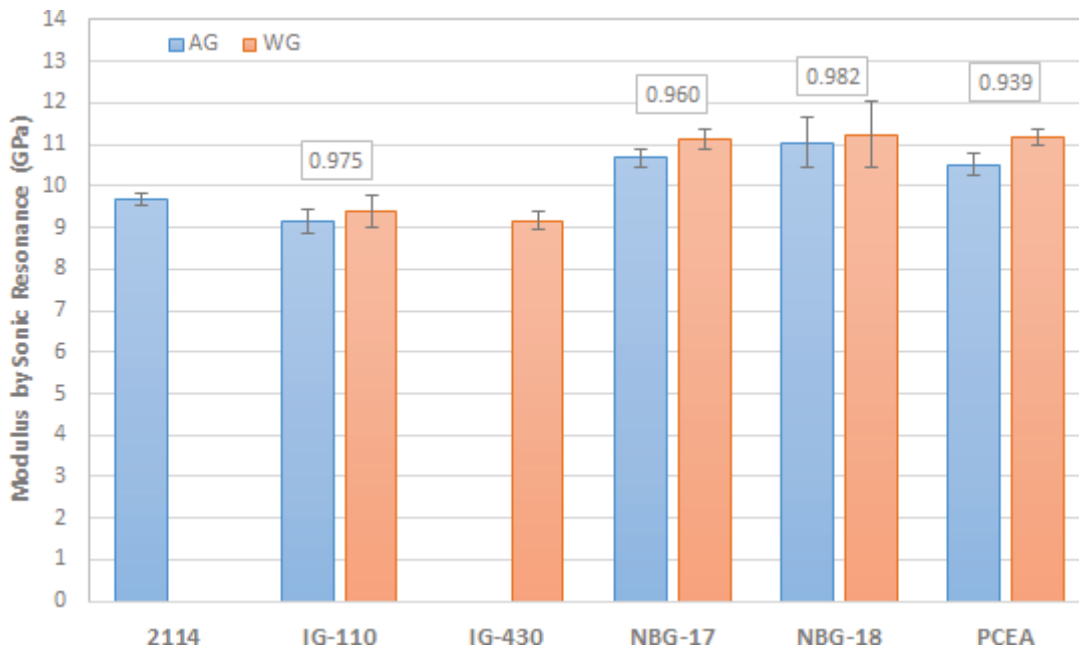


Figure 13. Young’s modulus calculated by the fundamental frequency method for the major graphite grades. The anisotropy ratio is above each set of data bars. The error bars represent ± 1 standard deviation. Grades 2114 and IG-430 only have one grain orientation.

4.5. Thermal Expansion

The mean coefficient of thermal expansion data from the pencil specimens and piggyback specimens are plotted in Figure A-42–Figure A-48 and Figure A-50–Figure A-55. Plots of CTE for specimens previously measured for AGC-2 post-irradiation or AGC-5 pre-irradiation can be found in INL/EXT-15-36244, “AGC-2 Specimen Post- Irradiation Data Package Report,” and INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report,” respectively.

Statistical evaluation of the CTE data was performed at a measurement temperature of 500°C for each graphite grade. The dashed lines in these plots indicate the upper and lower IQR limits. Table B-5 and Table B-9 contains values for the mean, standard deviation, COV, median, and upper/lower IQR limits for the data evaluated at 500°C.

As the statistics tables show, CTE data at the 500°C measurement temperature are well-behaved, with every grade’s COV equal to or less than 4%. When looking at both with-grain and against-grain data, PCEA had the largest COV at 4%, while NBG-18 and 2114 each had COVs of less than 1%.

Figure 14 shows the average of all the specimens across all the measurement temperatures, with error bars indicating ± 1 standard deviation. Every grade shows an increase with temperature in a near linear fashion between 100 and 1,000°C.

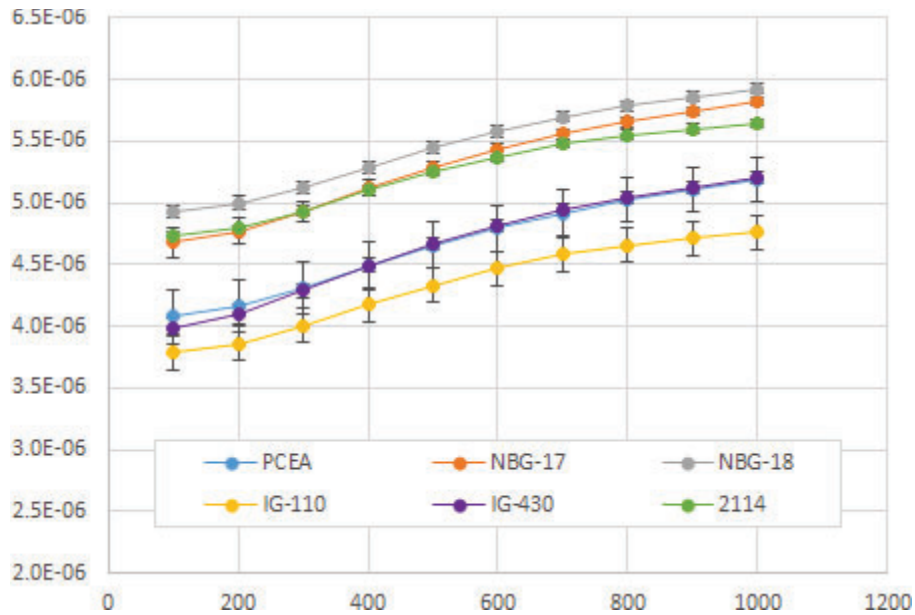


Figure 14. Mean CTE for all grades of graphite in HDG-1 as a function of temperature. The error bars represent ± 1 standard deviation.

Measurements of CTE were performed on both with-grain and against-grain specimens for grades NBG-17, NBG-18, PCEA, and IG-110. Figure 15 shows the average CTE value measured at 500°C, along with the anisotropy ratio for each grade of graphite (if applicable). PCEA showed the largest difference in CTE values between grain orientations, while NBG-18 showed the smallest.

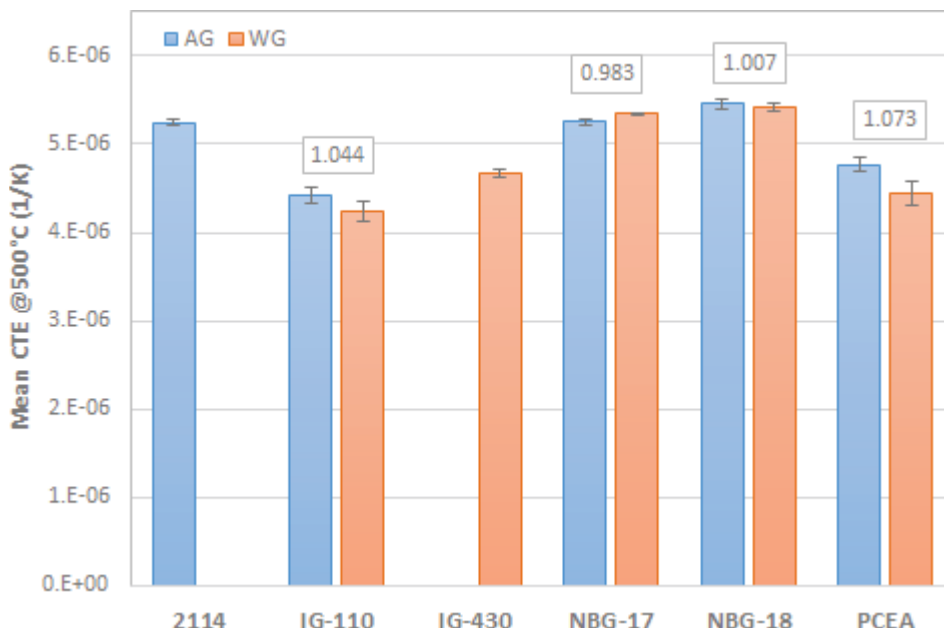


Figure 15. Mean CTE at 500°C along with the anisotropy ratio for pencil specimens as a function of temperature.

4.6. Thermal Diffusivity

The only new thermal diffusivity measurements made for HDG-1 were on the newly machined IG-430 piggyback specimens. Data plots of thermal diffusivity for IG-430 are shown in Figure 16 and Figure A-49. Plots of thermal diffusivity for specimens previously measured for AGC-2 post-irradiation or AGC-5 pre-irradiation can be found in INL/EXT-15-36244, “AGC-2 Specimen Post-Irradiation Data Package Report,” and INL/EXT-18-45226, “AGC-5 Graphite Pre-irradiation Data Analysis Report,” respectively.

As with the CTE data, only those diffusivity measurements taken at 500°C were statistically evaluated. Table B-8 contains values for the mean, standard deviation, COV, median, and lower/upper IQR limits. The COV for IG-430 is low: 2.1%. This is reflected in the tight grouping in Figure 16. No outliers were found after performing IQR analysis.

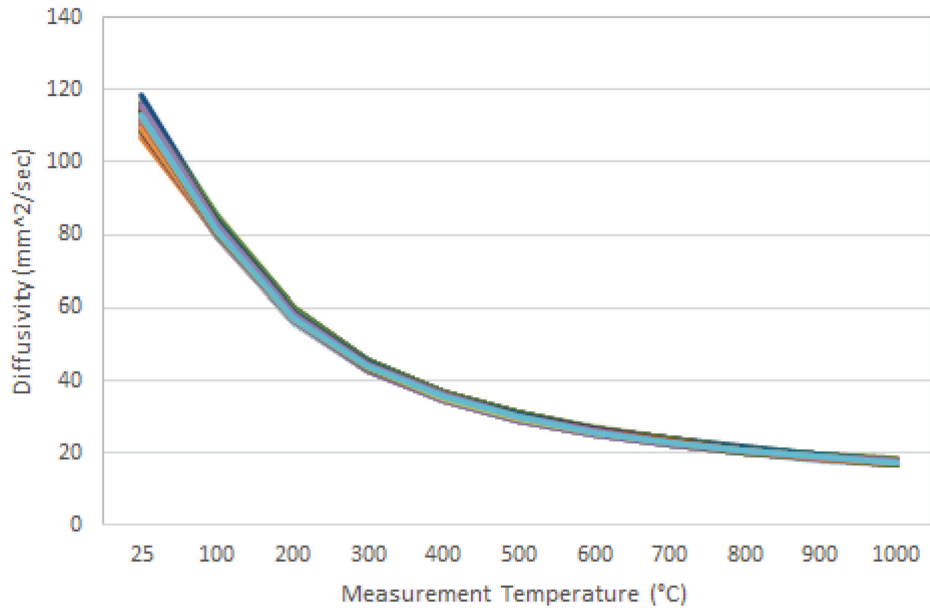


Figure 16. Thermal diffusivity for IG-430 as a function of measurement temperature.

Figure 17 shows the thermal diffusivity measured at 500°C vs. the specimen density. In general, as the density of a specimen increases, so does its diffusivity.

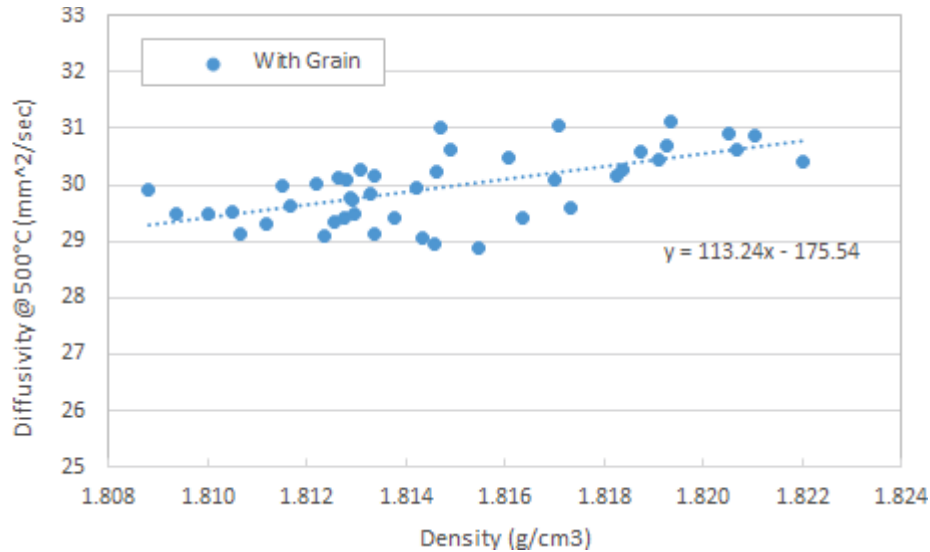


Figure 17. Diffusivity at measurement temperature 500°C vs. density for IG-430 piggyback specimens.

5. REFERENCES

1. T. Burchell, R. Bratton, W. Windes, *NGNP Graphite Selection and Acquisition Strategy*, ORNL/TM-2007/153, September 2007.
2. W. Windes, T. Burchell, R. Bratton, “Graphite Technology Development Plan,” PLN-2497, Rev. 1, October 2010.
3. R. L. Bratton and T. D. Burchell, *NGNP Graphite Testing and Qualification Specimen Selection Strategy*, INL/EXT-05-00269, May 2005.
4. Work instruction ART/AGC-WI-001, “HDG-1 Specimen Fabrication,” Rev. 2-7-19.
5. Work instruction ART/AGC=WI=002, “HDG-1 HOPG and Pencil Can Fabrication and Loading,” Rev. 4-25-19.
6. J. Brookman, P. Humrickhouse, V. Patel, and J. Navarro, *AGC Uncertainty Analysis*, INL/EXT-19-55576, Rev. 0, September 2019.
7. Work Instruction ART/AGC-WI-004 “HDG-1 Flux Wire V-Can Fabrication and Assembly” Rev. 0 12-5-19.
8. Work Instruction ART/AGC-WI-005 “HDG-1 Shipping Tube Loading” Rev. 0, 11-14-19.
9. PLN-4657, “AGC-2 Graphite Specimen Post-irradiation Characterization Plan”, 02-13-14, Rev. 0.
10. PLN-5580, “AGC-5 Graphite Specimen Pre-Irradiation Characterization Plan”, 3-26-18, Rev. 0.
11. LWP-13455, “Control of Measuring and Test Equipment,” Rev. 4, December 10, 2015.
12. ASTM C559-16, “Standard Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles,” ASTM International, 2016.
13. ASTM C611-98 (2016), “Standard Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature,” ASTM International, 2016.
14. ASTM C769-98(2005), “Standard Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining an Approximate Value of Young’s Modulus,” ASTM International, 2005.

15. ASTM C747-16, “Standard Test Method for Moduli of Elasticity and Fundamental Frequencies of Carbon and Graphite Materials by Sonic Resonance,” ASTM International, 2016.
16. ASTM E228-17, “Standard Test Method for Linear Expansion of Solid Materials with a Push-Rod Dilatometer,” ASTM International, 2017.
17. ASTM E1461-13, “Standard Test Method for Thermal Diffusivity by the Flash Method,” ASTM International, 2013.
18. R. D. Cowan, “Pulse Method of Measuring Thermal Diffusivity at High Temperatures,” *Journal of Applied Physics*, Vol. 34, No. 4, 1963, p. 926.
19. Y. S. Touloukian, *Thermophysical Properties of Matter—Thermal Diffusivity*, John Wiley & Sons Ltd., May 6, 1973.

Appendix A

HDG-1 Pre-Irradiation Pencil Specimen Data

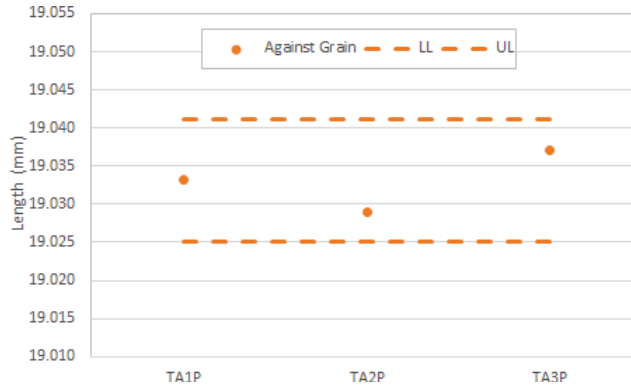


Figure A-1. 2114 pencil specimen length.

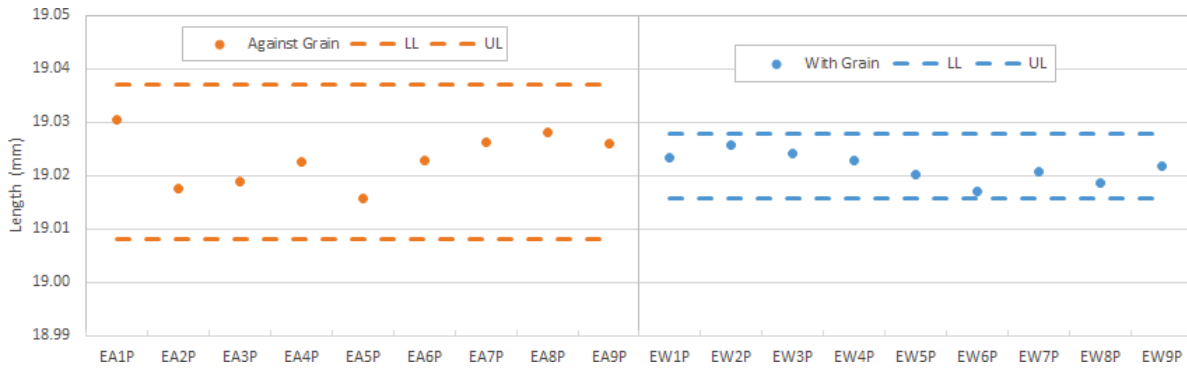


Figure A-2. IG-110 pencil specimen length.

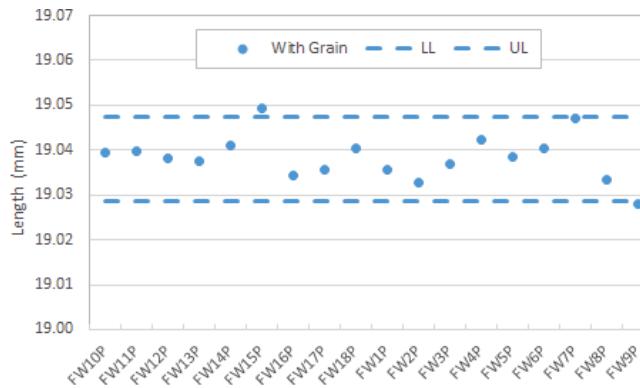


Figure A-3. IG-430 pencil specimen length.

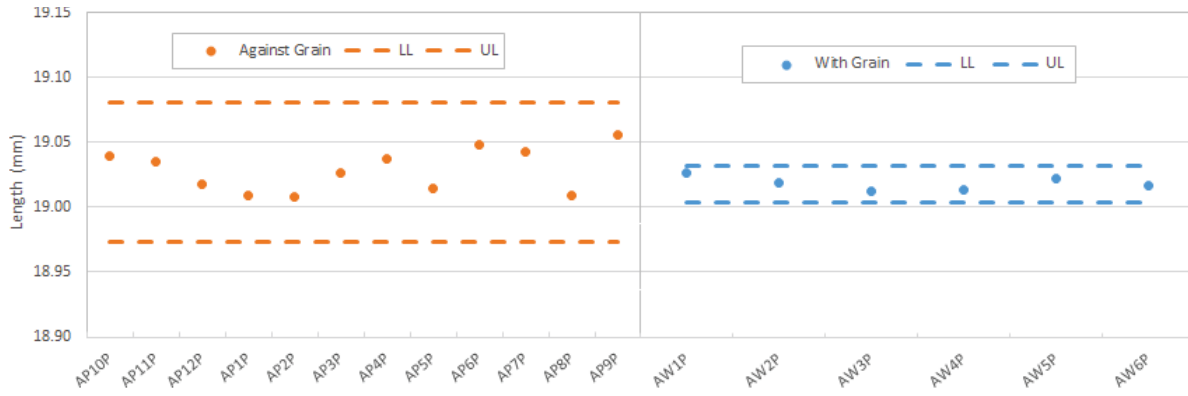


Figure A-4. NBG-17 pencil specimen length.

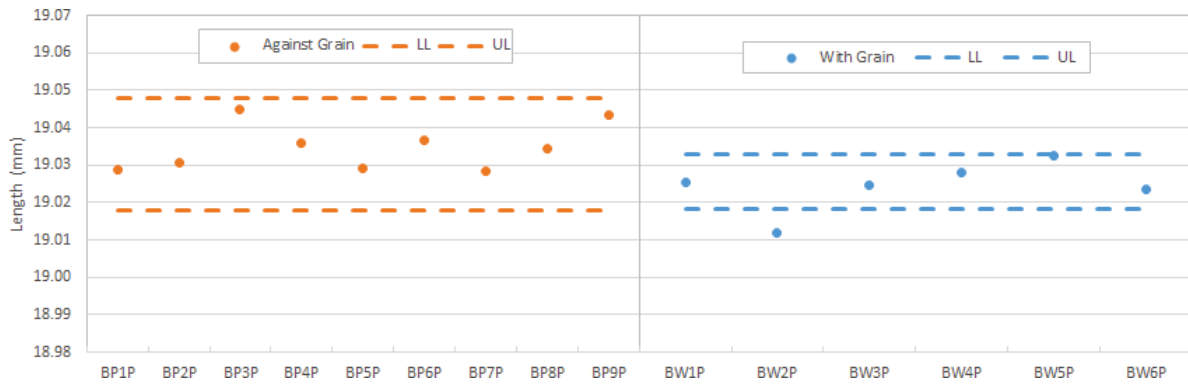


Figure A-5. NBG-18 pencil specimen length.

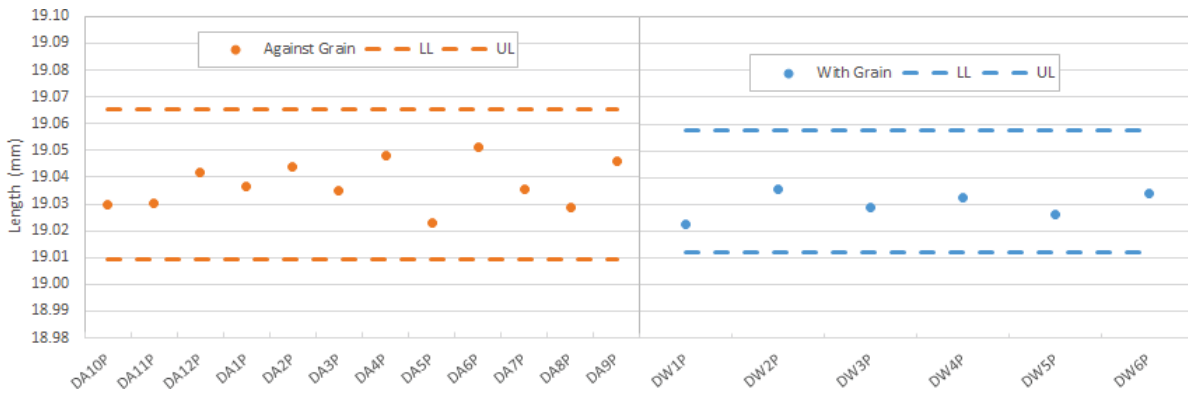


Figure A-6. PCEA pencil specimen length.

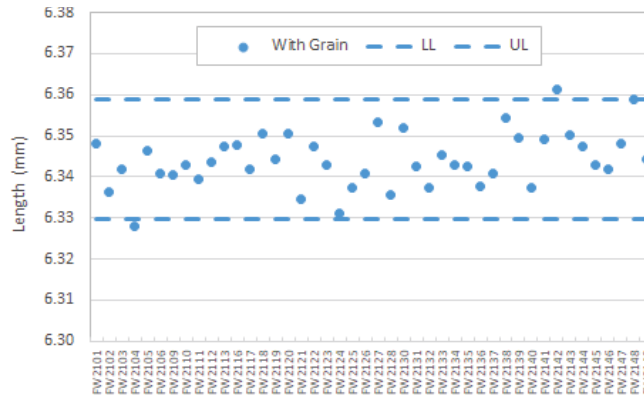


Figure A-7. IG-430 piggyback specimen length.

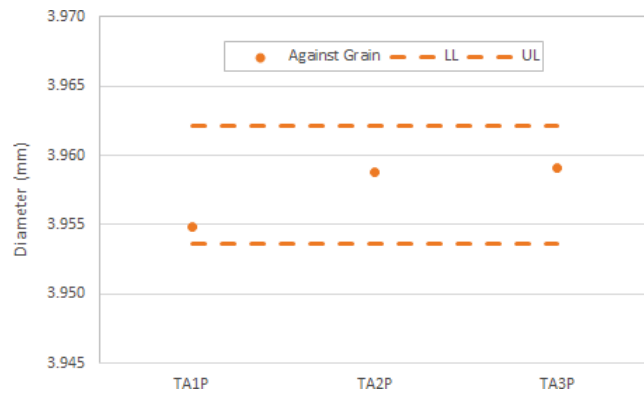


Figure A-8. 2114 pencil specimen diameter.

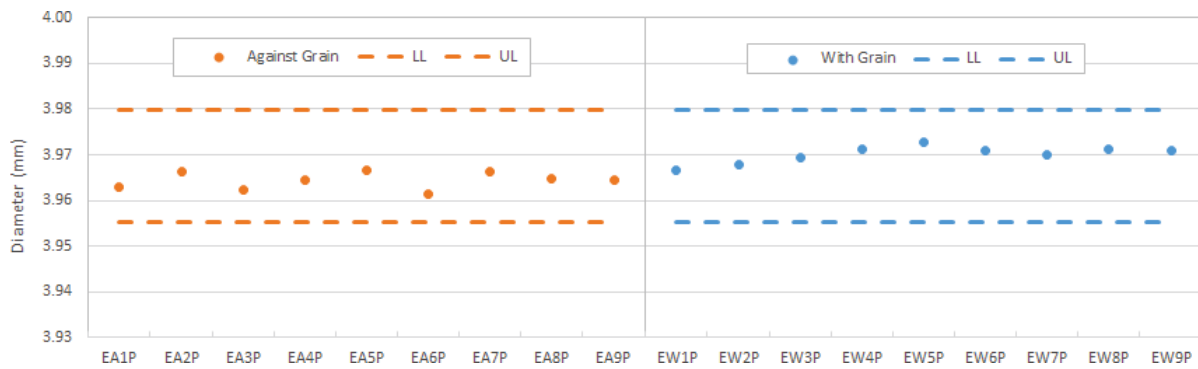


Figure A-9. IG-110 pencil specimen diameter.

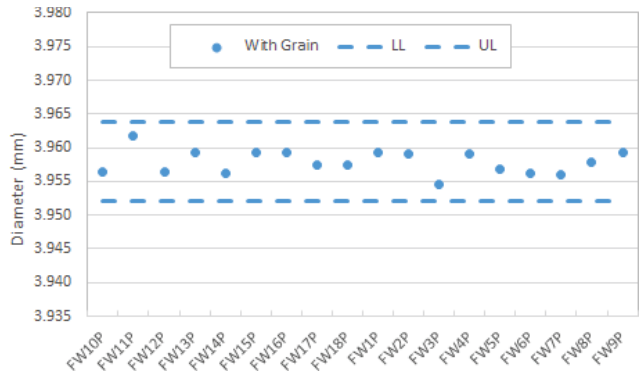


Figure A-10. IG-430 pencil specimen diameter.

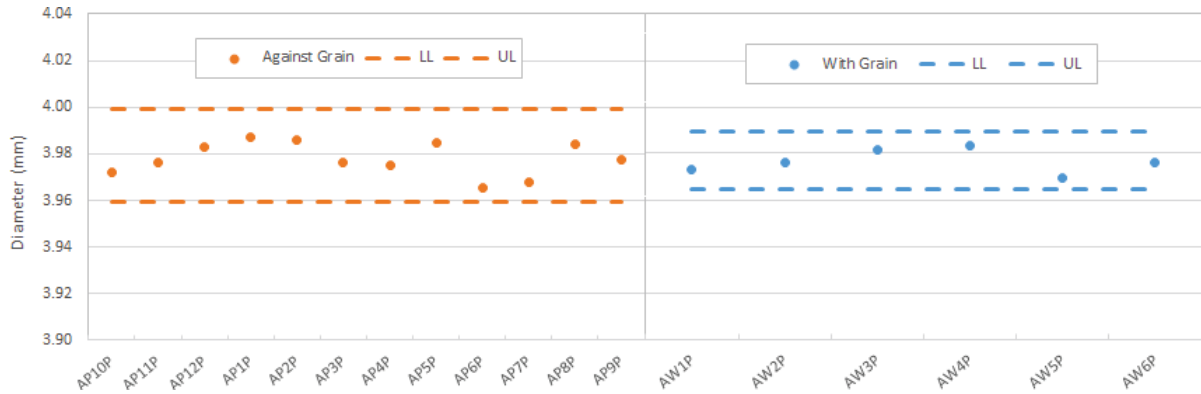


Figure A-11. NBG-17 pencil specimen diameter.



Figure A-12. NBG-18 pencil specimen diameter.

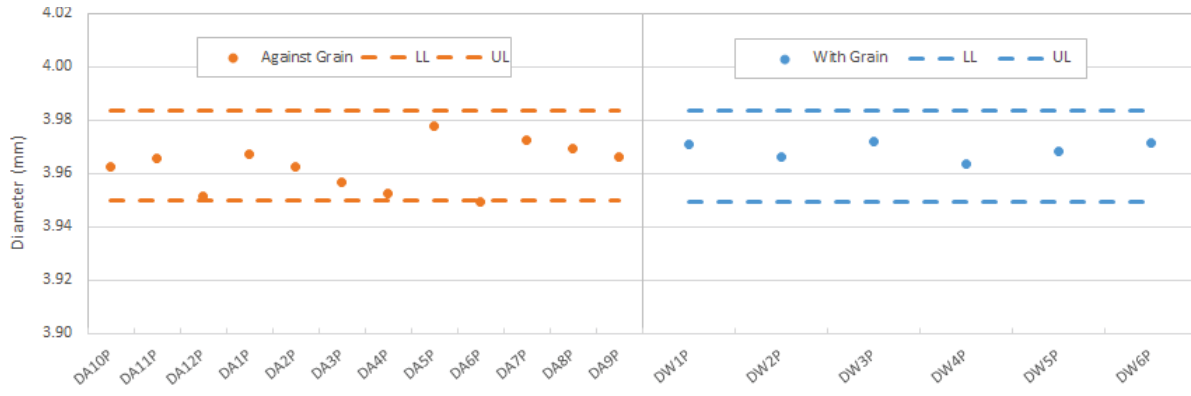


Figure A-13. PCEA pencil specimen diameter.

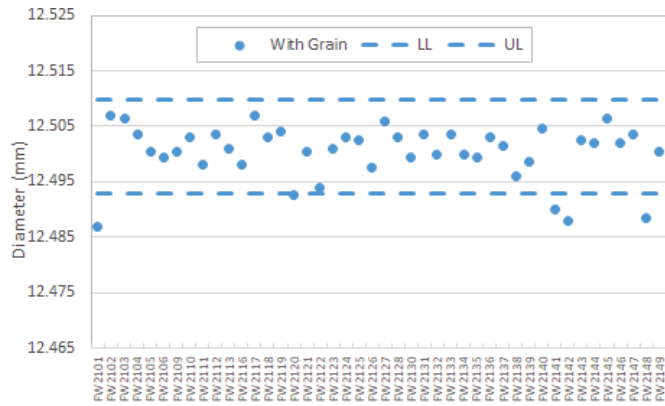


Figure A-14. IG-430 piggyback specimen diameter.

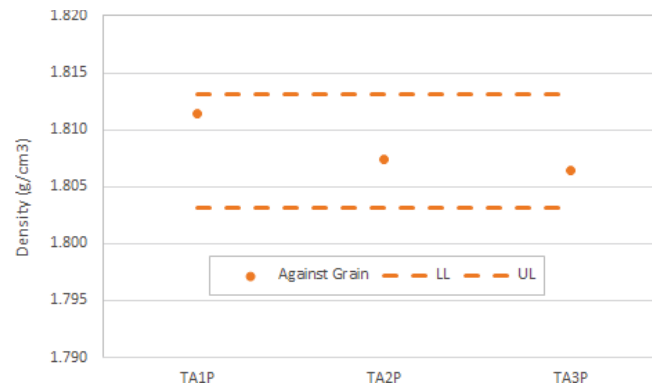


Figure A-15. 2114 pencil specimen density.

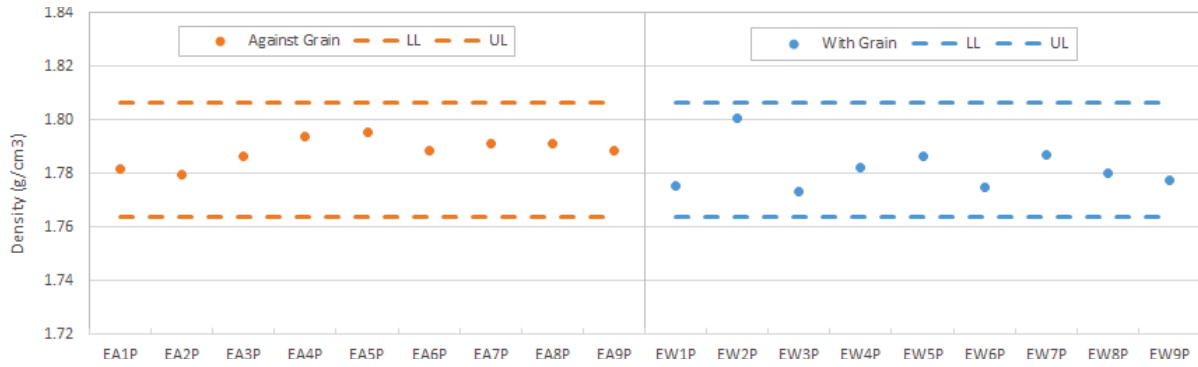


Figure A-16. IG-110 pencil specimen density.

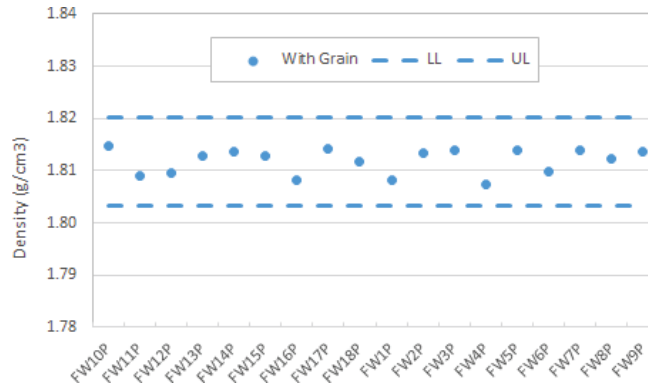


Figure A-17. IG-430 pencil specimen density.

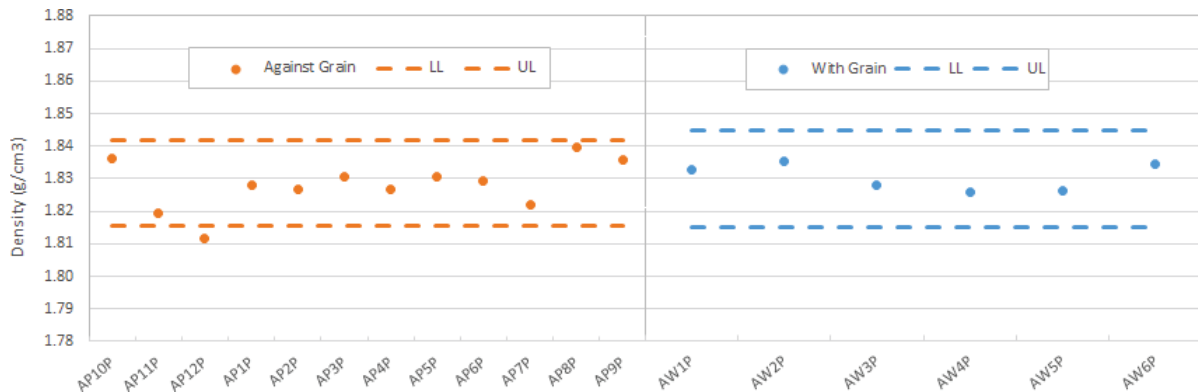


Figure A-18. NBG-17 pencil specimen density.



Figure A-19. NBG-18 pencil specimen density.

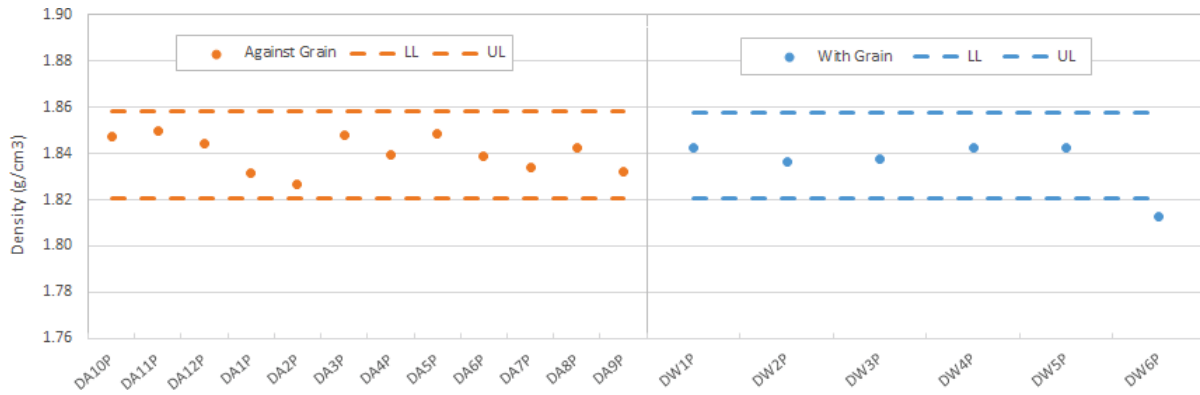


Figure A-20. PCEA pencil specimen density.

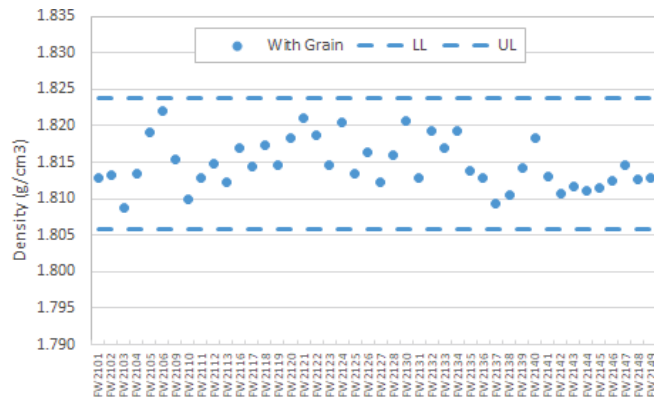


Figure A-21. IG-430 piggyback specimen density.

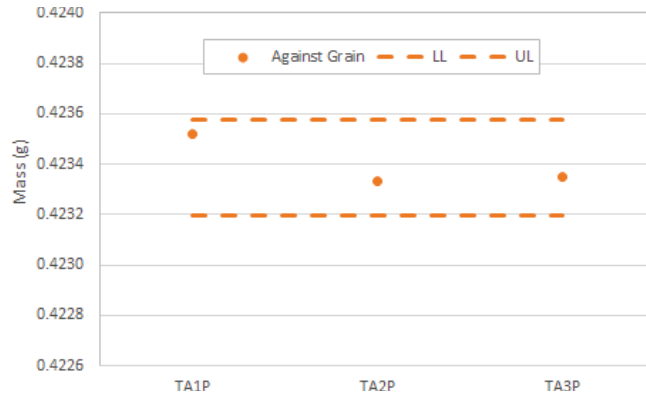


Figure A-22. 2114 pencil specimen mass.

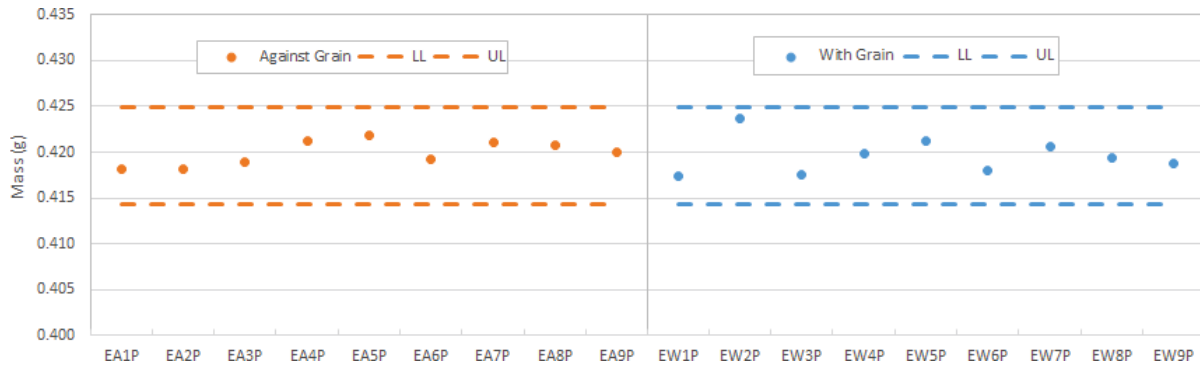


Figure A-23. IG-110 pencil specimen mass.

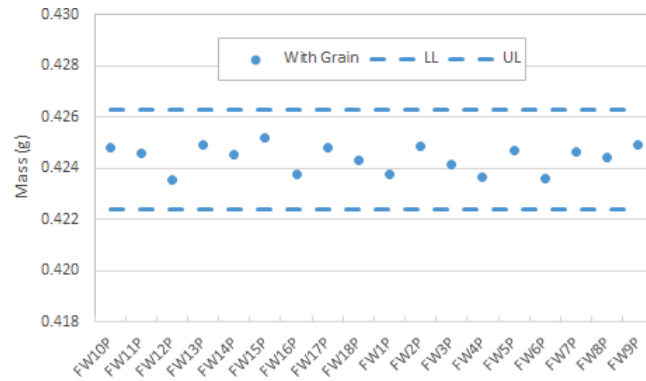


Figure A-24. IG-430 pencil specimen mass.

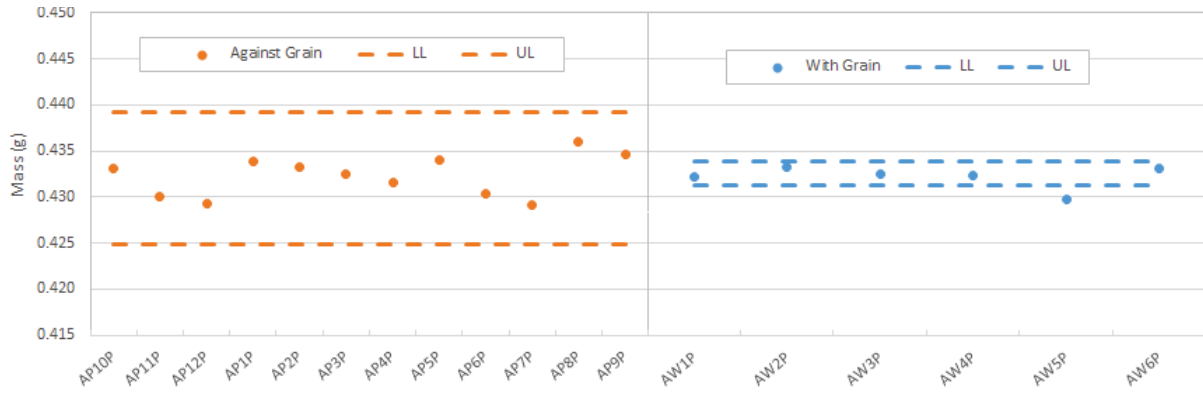


Figure A-25. NBG-17 pencil specimen mass.



Figure A-26. NBG-18 pencil specimen mass.

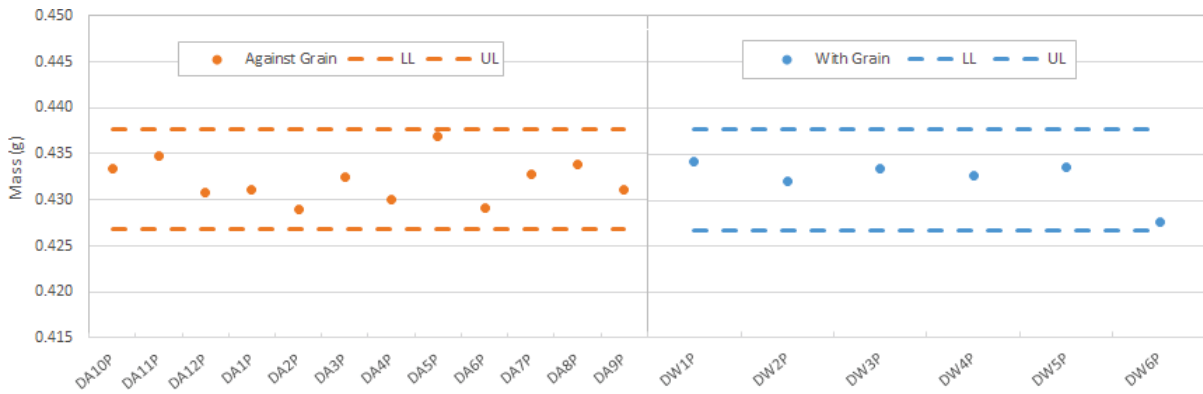


Figure A-27. PCEA pencil specimen mass.

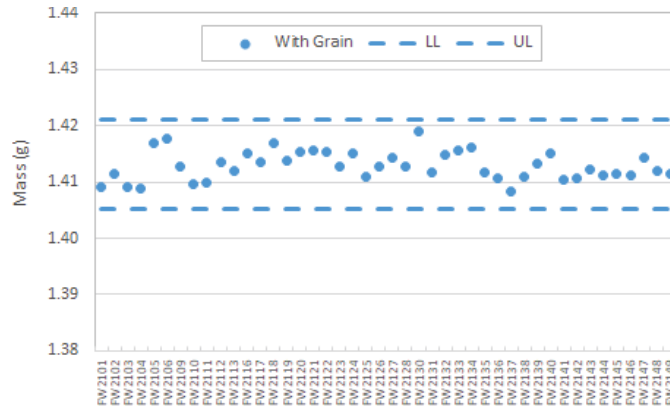


Figure A-28. IG-430 piggyback specimen mass.

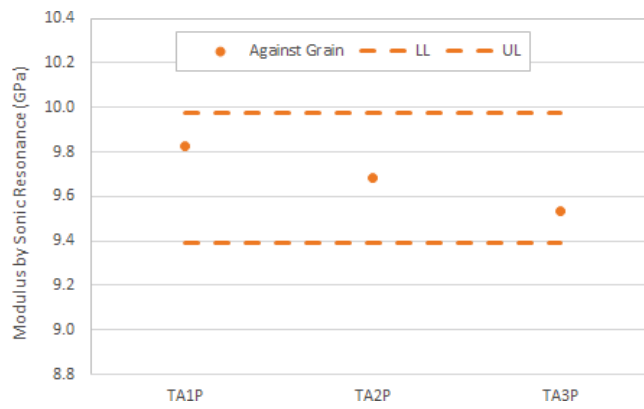


Figure A-29. 2114 pencil specimen modulus by sonic resonance method.

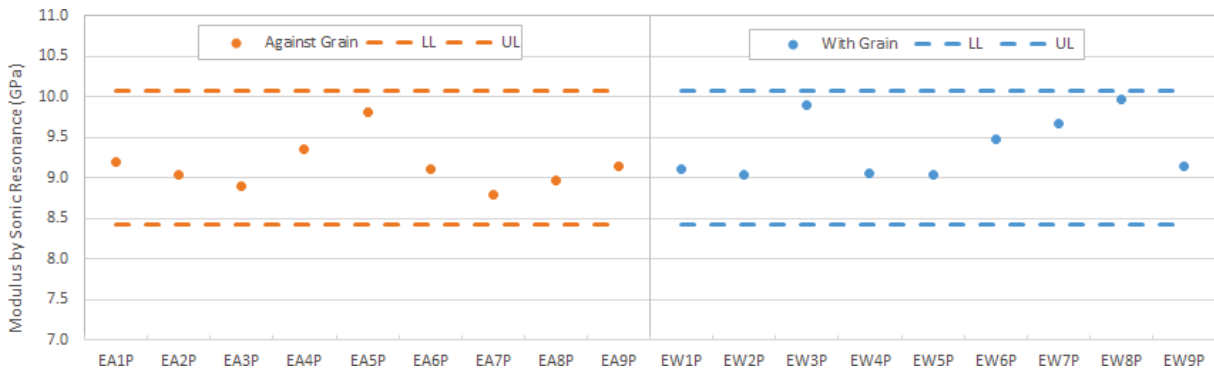


Figure A-30. IG-110 pencil specimen modulus by sonic resonance method.

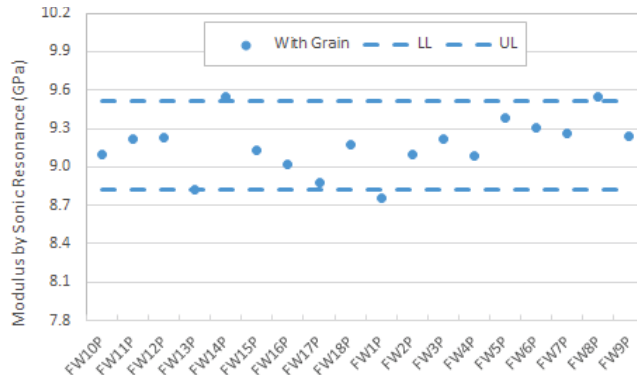


Figure A-31. IG-430 pencil specimen modulus by sonic resonance method.

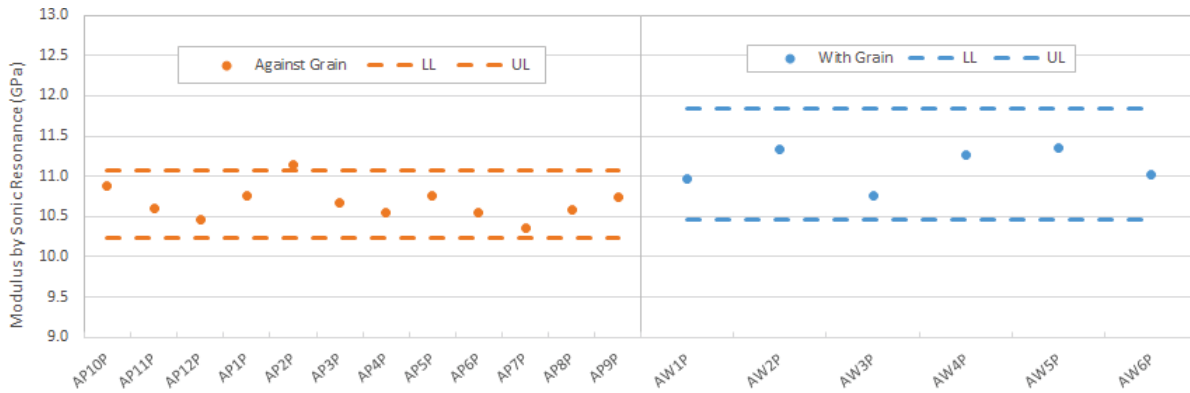


Figure A-32. NBG-17 pencil specimen modulus by sonic resonance method.

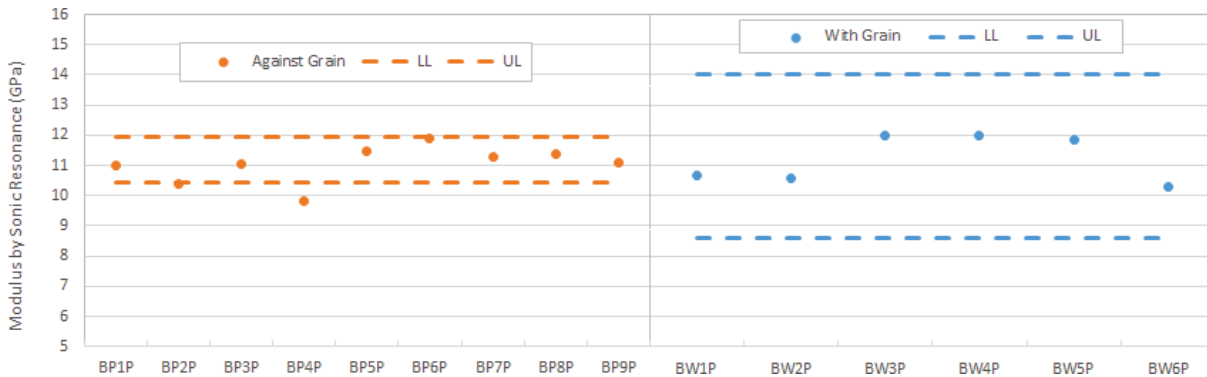


Figure A-33. NBG-18 pencil specimen modulus by sonic resonance method.

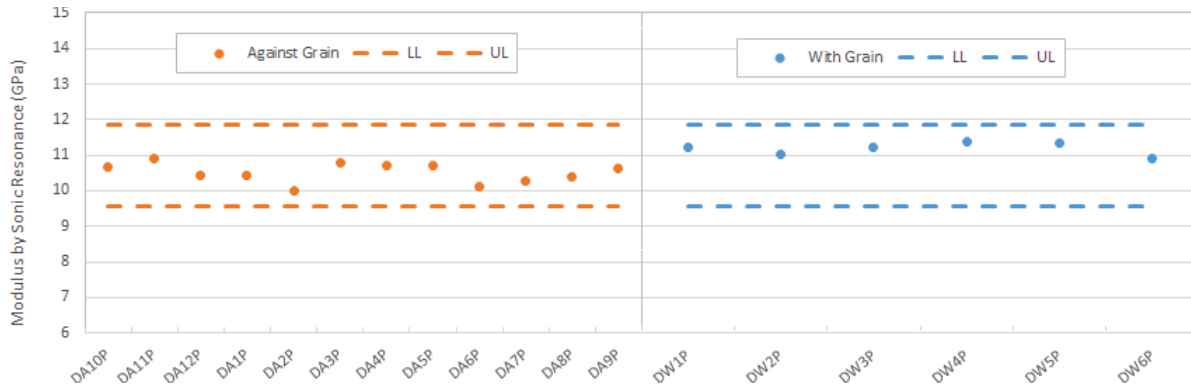


Figure A-34. PCEA pencil specimen modulus by sonic resonance method.

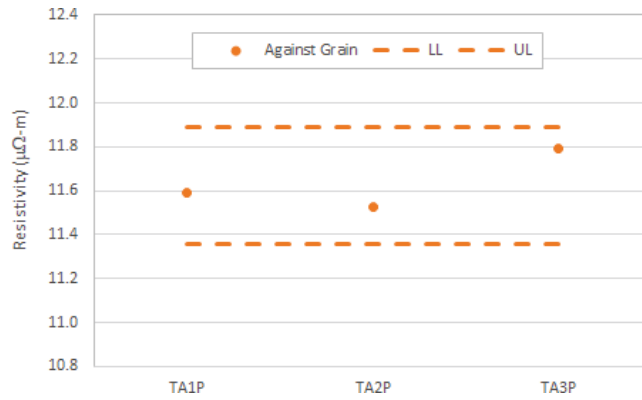


Figure A-35. 2114 pencil specimen resistivity.



Figure A-36. IG-110 pencil specimen resistivity.

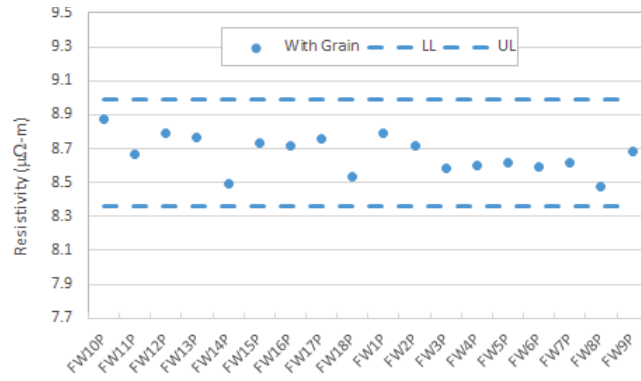


Figure A-37. IG-430 pencil specimen resistivity.

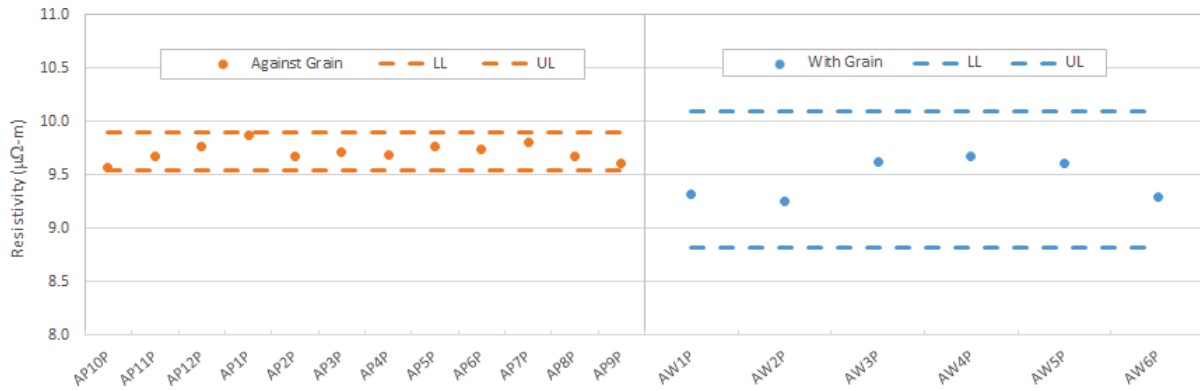


Figure A-38. NBG-17 pencil specimen resistivity.

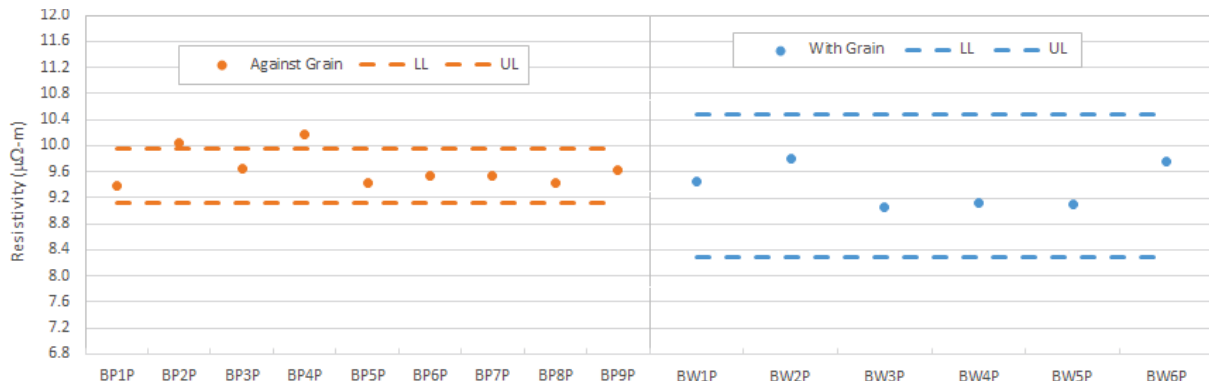


Figure A-39. NBG-18 pencil specimen resistivity.

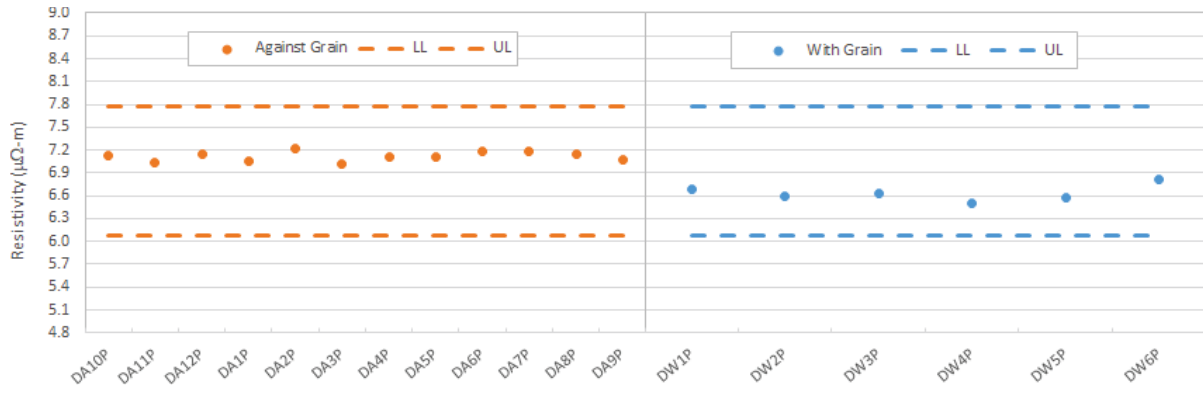


Figure A-40. PCEA pencil specimen resistivity.

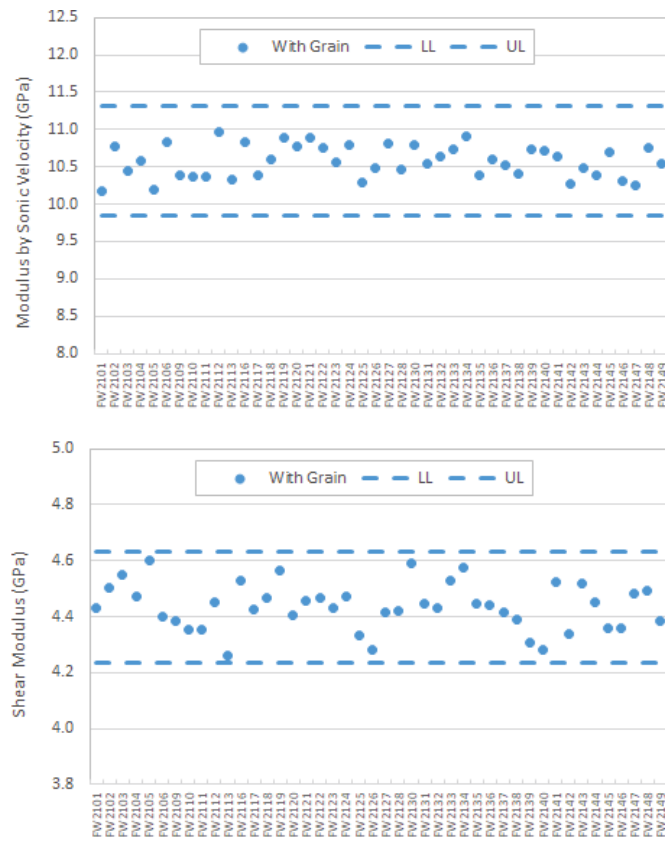


Figure A-41. IG-430 piggyback Young's and shear moduli.

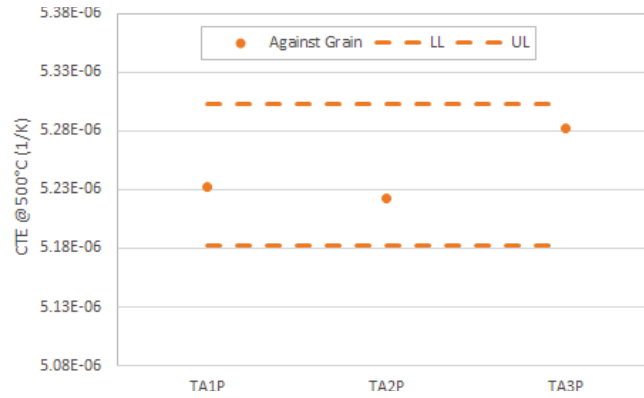


Figure A-42. 2114 pencil specimen mean CTE at 500°C.



Figure A-43. IG-110 pencil specimen mean CTE at 500°C.

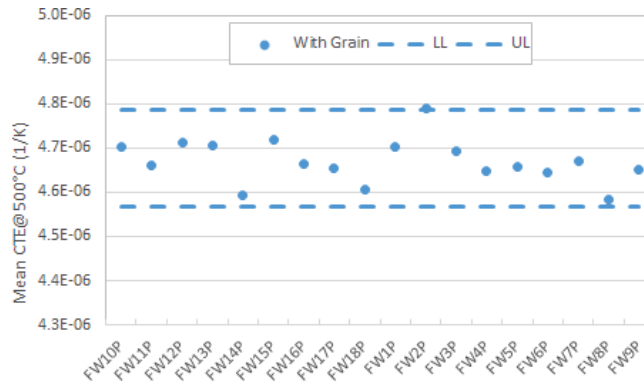


Figure A-44. IG-430 pencil specimen mean CTE at 500°C.

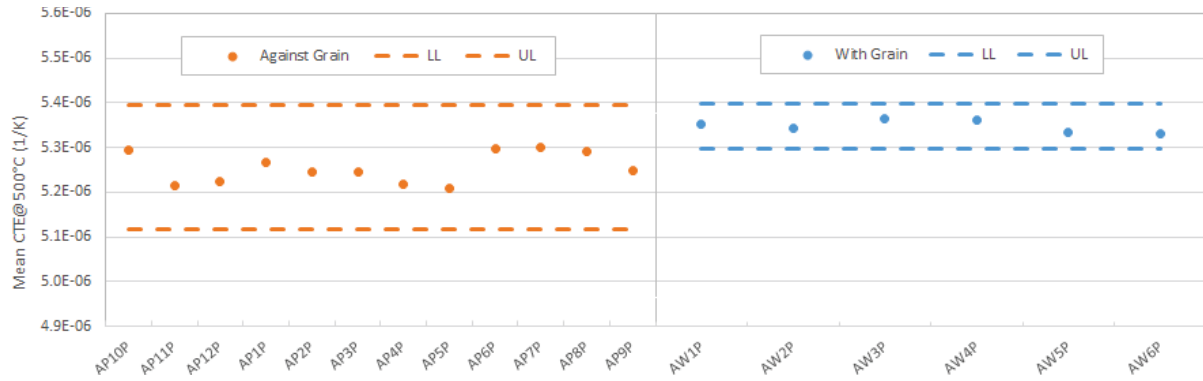


Figure A-45. NBG-17 pencil specimen mean CTE at 500°C.

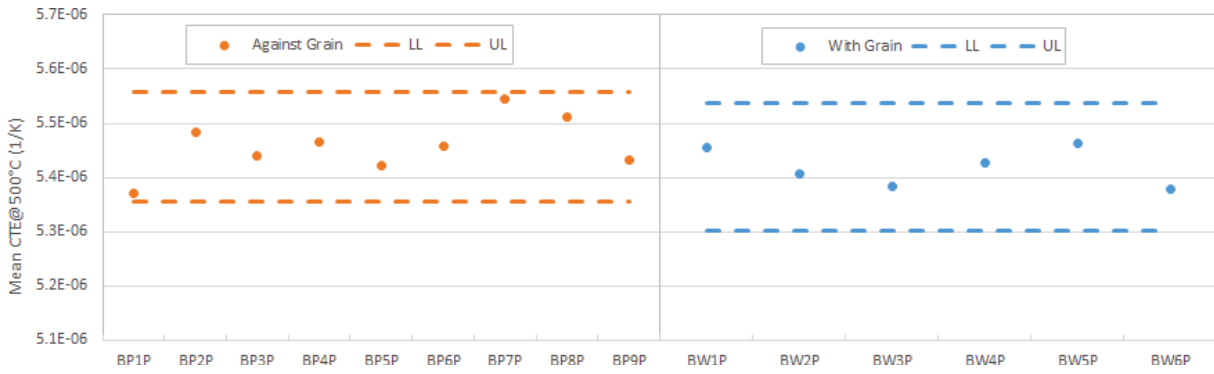


Figure A-46. NBG-18 pencil specimen mean CTE at 500°C.

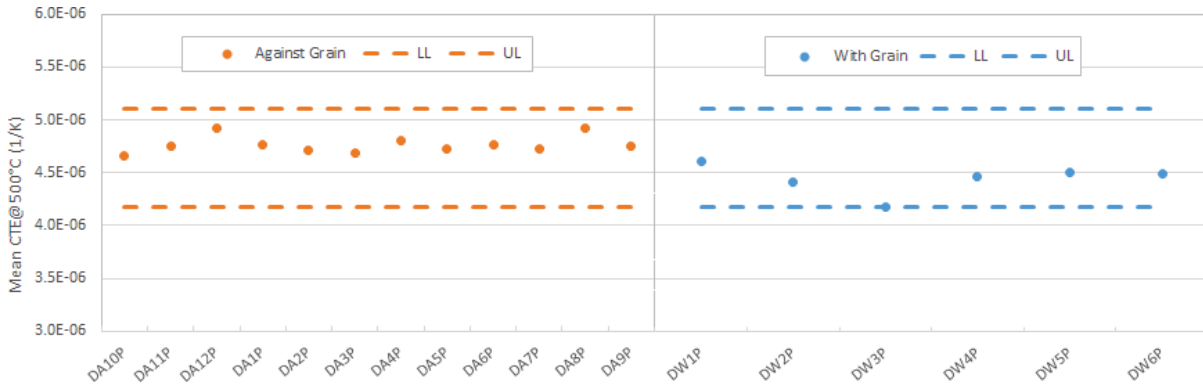


Figure A-47. PCEA pencil specimen mean CTE at 500°C.

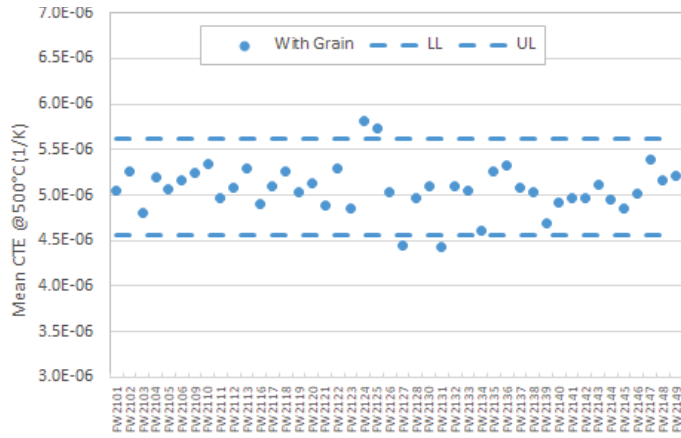


Figure A-48. IG-430 piggyback specimen mean CTE at 500°C.

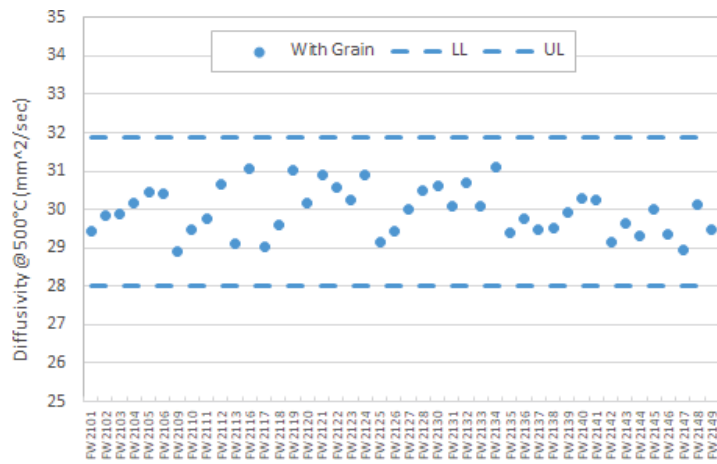


Figure A-49. IG-430 piggyback specimen diffusivity at 500°C.

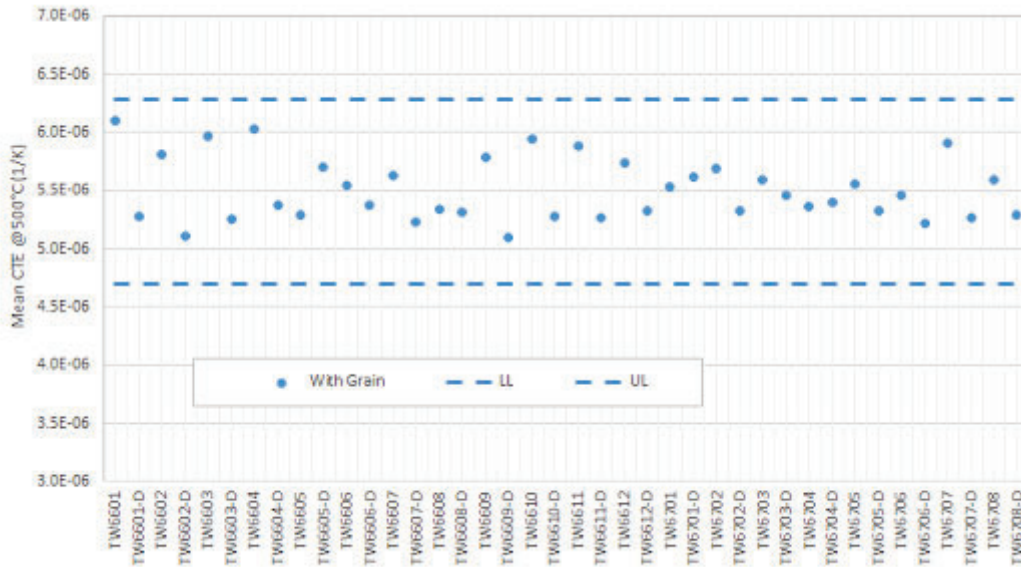


Figure A-50. 2114 piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).

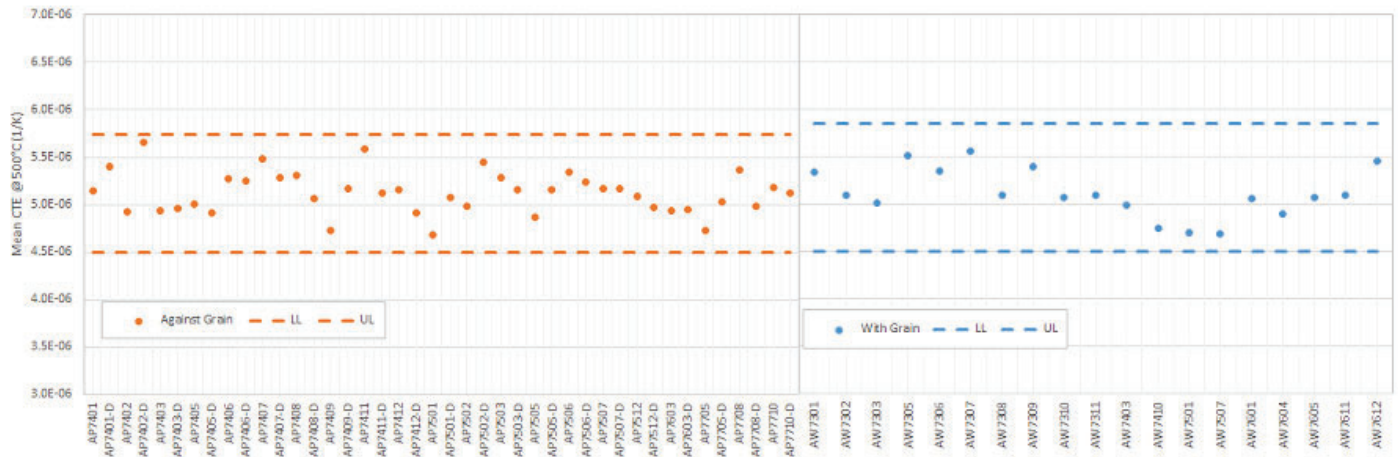


Figure A-51. NBG-17 piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).

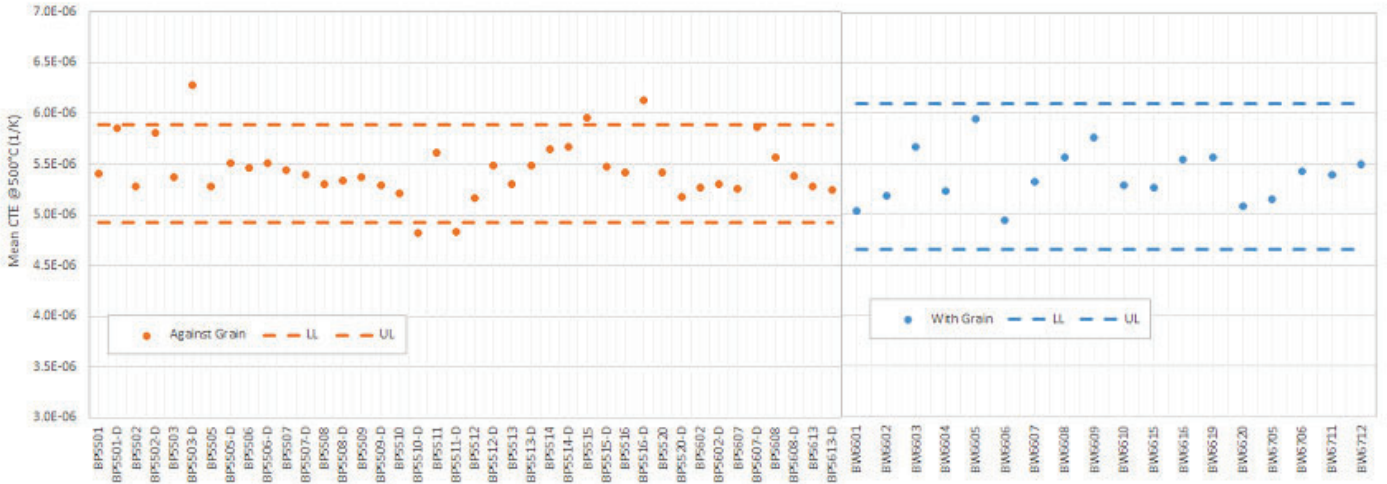


Figure A-52. NBG-18 piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).

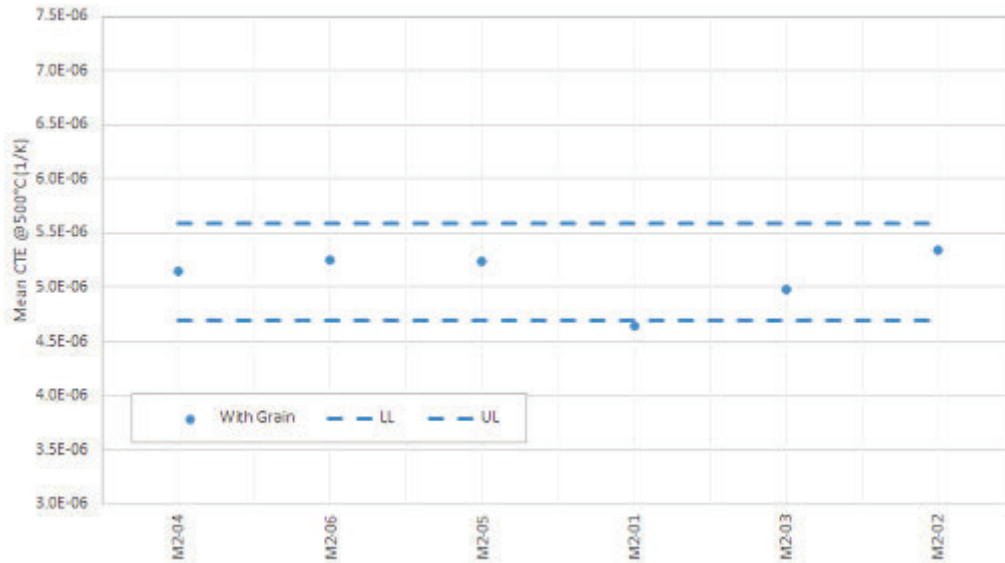


Figure A-53. NBG-25 piggyback specimen mean CTE at 500°C.

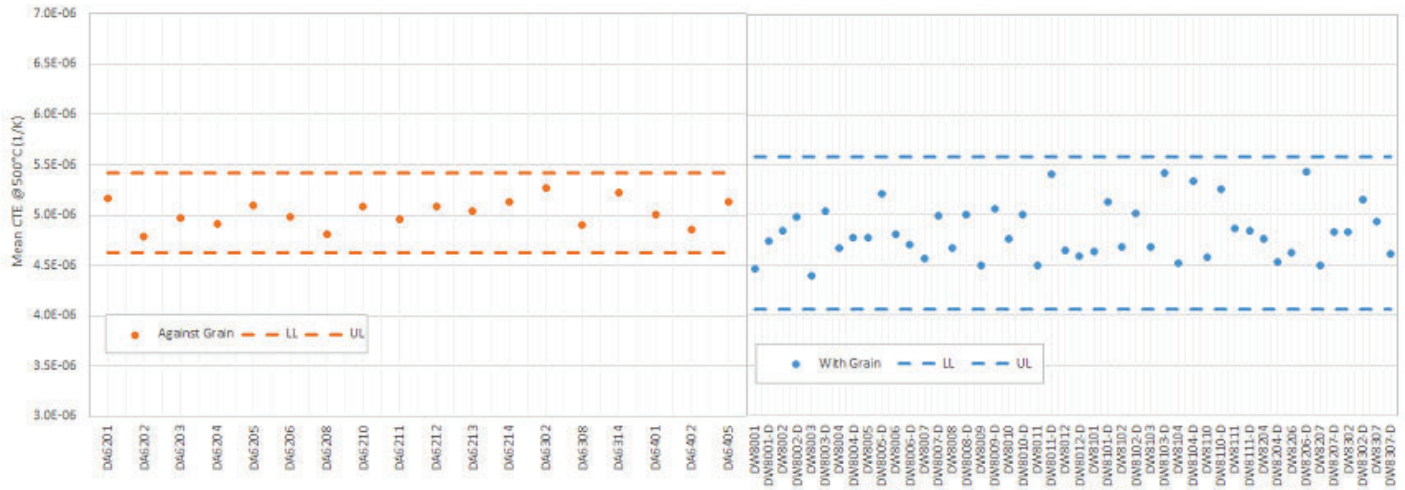


Figure A-54. PCEA piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).

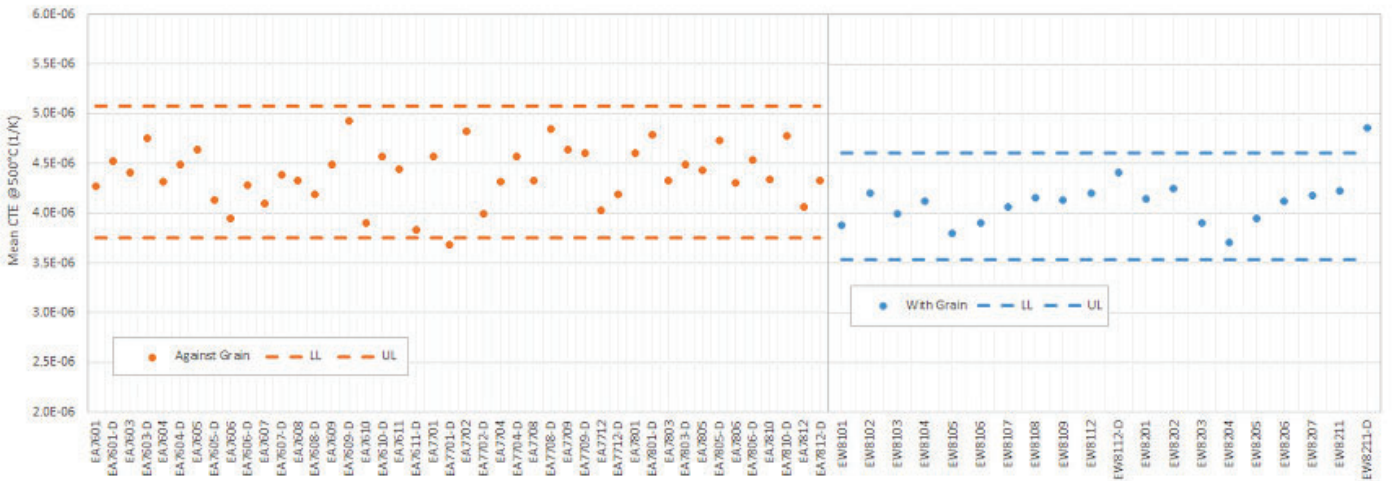


Figure A-55. PCEA piggyback specimen mean CTE at 500°C. (A “-D” designation indicates that CTE was measured in the diametral direction).

Appendix B

Summary of Statistical Parameters

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

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	19.0331	0.0040	0.02	19.0333	19.0411	19.0251
IG-110	19.0224	0.0040	0.02	19.0226	19.0345	19.0102
IG-430	19.0383	0.0050	0.03	19.0384	19.0473	19.0285
NBG-17	19.0253	0.0145	0.08	19.0208	19.0718	18.9788
NBG-18	19.0305	0.0081	0.04	19.0290	19.0474	19.0144
PCEA	19.0351	0.0083	0.04	19.0345	19.0578	19.0121

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	19.0216	0.0027	0.01	19.0218	19.0278	19.0158
IG-430	19.0383	0.0050	0.03	19.0384	19.0473	19.0285
NBG-17	19.0185	0.0054	0.03	19.0183	19.0322	19.0034
NBG-18	19.0243	0.0069	0.04	19.0250	19.0328	19.0183
PCEA	19.0302	0.0050	0.03	19.0309	19.0440	19.0170

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	19.0331	0.0040	0.02	19.0333	19.0411	19.0251
IG-110	19.0231	0.0050	0.03	19.0228	19.0371	19.0081
IG-430	---	---	---	---	---	---
NBG-17	19.0287	0.0165	0.09	19.0309	19.0803	18.9736
NBG-18	19.0346	0.0061	0.03	19.0343	19.0478	19.0178
PCEA	19.0375	0.0087	0.05	19.0360	19.0652	19.0095

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

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	3.9576	0.0024	0.06	3.9588	3.9621	3.9536
IG-110	3.9672	0.0035	0.09	3.9666	3.9800	3.9553
IG-430	3.9579	0.0018	0.04	3.9577	3.9638	3.9520
NBG-17	3.9775	0.0064	0.16	3.9763	3.9969	3.9598
NBG-18	3.9655	0.0026	0.07	3.9646	3.9731	3.9581
PCEA	3.9650	0.0079	0.20	3.9664	3.9836	3.9497

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	3.9701	0.0019	0.05	3.9710	3.9739	3.9669
IG-430	3.9579	0.0018	0.04	3.9577	3.9638	3.9520
NBG-17	3.9766	0.0051	0.13	3.9762	3.9895	3.9646
NBG-18	3.9637	0.0009	0.02	3.9638	3.9664	3.9612
PCEA	3.9691	0.0034	0.09	3.9700	3.9788	3.9600

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	3.9576	0.0024	0.06	3.9588	3.9621	3.9536
IG-110	3.9644	0.0019	0.05	3.9645	3.9713	3.9578
IG-430	---	---	---	---	---	---
NBG-17	3.9779	0.0071	0.18	3.9769	3.9995	3.9591
NBG-18	3.9668	0.0026	0.07	3.9664	3.9731	3.9611
PCEA	3.9629	0.0088	0.22	3.9641	3.9864	3.9374

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

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	0.4234	0.0001	0.02	0.4234	0.4236	0.4232
IG-110	0.4198	0.0017	0.40	0.4196	0.4250	0.4143
IG-430	0.4244	0.0005	0.12	0.4246	0.4263	0.4224
NBG-17	0.4323	0.0019	0.45	0.4326	0.4374	0.4266
NBG-18	0.4303	0.0050	1.15	0.4305	0.4419	0.4201
PCEA	0.4322	0.0023	0.54	0.4326	0.4377	0.4268

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	0.4196	0.0020	0.48	0.4194	0.4246	0.4142
IG-430	0.4244	0.0005	0.12	0.4246	0.4263	0.4224
NBG-17	0.4323	0.0013	0.30	0.4325	0.4340	0.4313
NBG-18	0.4331	0.0039	0.91	0.4344	0.4441	0.4219
PCEA	0.4323	0.0024	0.55	0.4331	0.4357	0.4301

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	0.4234	0.0001	0.02	0.4234	0.4236	0.4232
IG-110	0.4199	0.0014	0.33	0.4200	0.4243	0.4157
IG-430	---	---	---	---	---	---
NBG-17	0.4323	0.0022	0.52	0.4328	0.4393	0.4248
NBG-18	0.4285	0.0049	1.14	0.4302	0.4354	0.4240
PCEA	0.4321	0.0024	0.55	0.4318	0.4380	0.4262

Table B-4. Pencil specimen density (g/cm³) summary statistics.

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.8084	0.0026	0.15	1.8074	1.8131	1.8032
IG-110	1.7852	0.0077	0.43	1.7863	1.8063	1.7637
IG-430	1.8118	0.0025	0.14	1.8129	1.8202	1.8033
NBG-17	1.8287	0.0067	0.37	1.8286	1.8455	1.8143
NBG-18	1.8309	0.0215	1.17	1.8289	1.8751	1.7925
PCEA	1.8388	0.0090	0.49	1.8410	1.8580	1.8207

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	1.7820	0.0086	0.48	1.7803	1.8029	1.7588
IG-430	1.8118	0.0025	0.14	1.8129	1.8202	1.8033
NBG-17	1.8301	0.0043	0.23	1.8300	1.8451	1.8150
NBG-18	1.8449	0.0165	0.89	1.8504	1.8931	1.7967
PCEA	1.8358	0.0114	0.62	1.8131	1.8507	1.8287

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	1.8084	0.0026	0.15	1.8074	1.8131	1.8032
IG-110	1.7884	0.0053	0.29	1.7886	1.7987	1.7789
IG-430	---	---	---	---	---	---
NBG-17	1.8280	0.0077	0.42	1.8286	1.8419	1.8155
NBG-18	1.8215	0.0199	1.09	1.8266	1.8453	1.8099
PCEA	1.8402	0.0077	0.42	1.8410	1.8680	1.8128

Table B-5. Creep specimen coefficient of thermal expansion (1/K) at 500°C summary statistics.

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.25E-06	3.21E-08	0.61	5.23E-06	5.30E-06	5.18E-06
IG-110	4.33E-06	1.37E-07	3.16	4.33E-06	4.67E-06	3.99E-06
IG-430	4.67E-06	5.00E-08	1.07	4.66E-06	4.79E-06	4.57E-06
NBG-17	5.29E-06	5.39E-08	1.02	5.29E-06	5.46E-06	5.11E-06
NBG-18	5.44E-06	4.87E-08	0.89	5.44E-06	5.54E-06	5.34E-06
PCEA	4.66E-06	1.88E-07	4.03	4.72E-06	5.11E-06	4.18E-06

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	4.24E-06	1.05E-07	2.49	4.26E-06	4.42E-06	0.00E+00
IG-430	4.67E-06	5.00E-08	1.07	4.66E-06	4.79E-06	4.57E-06
NBG-17	5.35E-06	1.46E-08	0.27	5.35E-06	5.40E-06	5.30E-06
NBG-18	5.42E-06	3.58E-08	0.66	5.42E-06	5.54E-06	5.30E-06
PCEA	4.44E-06	1.42E-07	3.20	4.47E-06	4.61E-06	4.30E-06

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.25E-06	3.21E-08	0.61	5.23E-06	5.30E-06	5.18E-06
IG-110	4.42E-06	9.44E-08	2.13	4.41E-06	4.68E-06	0.00E+00
IG-430	---	---	---	---	---	---
NBG-17	5.25E-06	3.48E-08	0.66	5.25E-06	5.40E-06	5.12E-06
NBG-18	5.46E-06	5.13E-08	0.94	5.46E-06	5.56E-06	5.36E-06
PCEA	4.76E-06	8.20E-08	1.72	4.75E-06	4.86E-06	4.64E-06

Table B-6. Pencil specimen modulus (GPa) by sonic resonance summary statistics.

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	9.68	0.15	1.51	9.69	9.98	9.39
IG-110	9.27	0.35	3.82	9.14	10.07	8.43
IG-430	9.17	0.22	2.35	9.19	9.52	8.83
NBG-17	10.82	0.30	2.80	10.76	11.63	9.96
NBG-18	11.13	0.67	6.03	11.11	13.22	9.08
PCEA	10.74	0.41	3.84	10.70	11.86	9.58

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	9.38	0.38	4.08	9.15	10.57	8.15
IG-430	9.17	0.22	2.35	9.19	9.52	8.83
NBG-17	11.12	0.24	2.14	11.14	11.84	10.46
NBG-18	11.24	0.79	7.06	11.26	13.98	8.59
PCEA	11.19	0.19	1.71	11.23	11.67	10.73

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	9.68	0.15	1.51	9.69	9.98	9.39
IG-110	9.15	0.30	3.27	9.12	9.56	8.61
IG-430	---	---	---	---	---	---
NBG-17	10.67	0.21	1.96	10.64	11.07	10.24
NBG-18	11.05	0.61	5.54	11.11	11.96	10.43
PCEA	10.51	0.27	2.61	10.54	11.19	9.87

Table B-7. Pencil specimen resistivity (mW-m) summary statistics.

All grain orientations	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	11.64	0.14	1.20	11.59	11.89	11.36
IG-110	9.66	0.42	4.36	9.68	10.70	8.69
IG-430	8.67	0.11	1.28	8.68	8.99	8.36
NBG-17	9.63	0.17	1.81	9.67	9.92	9.42
NBG-18	9.54	0.32	3.32	9.53	10.12	8.99
PCEA	6.96	0.25	3.57	7.07	7.78	6.07

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	9.43	0.37	3.95	9.49	10.27	8.73
IG-430	8.67	0.11	1.28	8.68	8.99	8.36
NBG-17	9.46	0.19	2.03	9.46	10.10	8.82
NBG-18	9.38	0.32	3.46	9.28	10.49	8.29
PCEA	6.63	0.11	1.62	6.61	6.79	6.46

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	11.64	0.14	1.20	11.59	11.89	11.36
IG-110	9.89	0.35	3.50	9.97	10.70	9.04
IG-430	---	---	---	---	---	---
NBG-17	9.71	0.08	0.84	9.70	9.90	9.54
NBG-18	9.64	0.28	2.90	9.53	9.96	9.12
PCEA	7.12	0.06	0.91	7.12	7.27	6.95

Table B-8. IG-430 piggyback specimen summary statistics.

	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
Length	6.3441	0.0067	0.11	6.3429	6.3590	6.3297
Diameter	12.5003	0.0049	0.04	12.5013	12.5099	12.4929
Density	1.8147	0.0034	0.19	1.8140	1.8239	1.8059
Mass	1.4129	0.0026	0.18	1.4127	1.4210	1.4051
Young's	10.58	0.2162	2.04	10.57	11.31	9.84
Shear	4.44	0.0834	1.88	4.44	4.63	4.24
CTE @ 500°	5.07E-06	2.65E-07	5.23	5.07E-06	5.61E-06	4.56E-06
Diff @ 500°C	29.95	0.6159	2.06	29.96	31.86	28.03

Table B-9. Piggyback specimen coefficient of thermal expansion (1/K) at 500°C summary statistics.

All Grains	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.51E-06	2.67E-07	4.84	5.44E-06	6.29E-06	4.70E-06
IG-110	4.31E-06	3.03E-07	7.03	4.31E-06	5.15E-06	3.50E-06
NBG-17	5.12E-06	2.32E-07	4.52	5.09E-06	5.75E-06	4.50E-06
NBG-18	5.43E-06	2.84E-07	5.22	5.40E-06	5.99E-06	4.84E-06
PCEA	4.89E-06	2.58E-07	5.29	4.87E-06	5.67E-06	4.09E-06

With Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	5.51E-06	2.67E-07	4.84	5.44E-06	6.29E-06	4.70E-06
IG-110	4.11E-06	2.45E-07	5.96	4.13E-06	4.60E-06	3.54E-06
NBG-17	5.11E-06	2.62E-07	5.12	5.09E-06	5.85E-06	4.49E-06
NBG-18	5.38E-06	2.65E-07	4.92	5.36E-06	6.10E-06	4.66E-06
PCEA	4.83E-06	2.75E-07	5.70	4.77E-06	5.58E-06	4.06E-06

Against Grain	Mean	Std Dev	CoV (%)	Median	Upper Limit	Lower Limit
2114	---	---	---	---	---	---
IG-110	4.39E-06	2.88E-07	6.56	4.40E-06	5.08E-06	3.75E-06
NBG-17	5.13E-06	2.20E-07	4.29	5.13E-06	5.74E-06	4.49E-06
NBG-18	5.45E-06	2.92E-07	5.37	5.40E-06	5.89E-06	4.93E-06
PCEA	5.02E-06	1.38E-07	2.74	5.02E-06	5.42E-06	4.62E-06

Appendix C

Final Loading Configuration for HDG-1 Specimens

Table C-1. Final loading configuration for HDG-1 specimens. The height (inches) is the distance from the reactor core centerline to the specimen's center of mass.

Stack 1							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
20.125	1	M2-01	PB	NBG-25	0.00	4.40	AG
19.500	1	TW5901	Creep	2114	0.00	4.98	WG
18.875	1	FW2101	PB	IG-430	0.00	4.98	WG
18.250	1	DW1 01	Creep	PCEA	2.31	7.95	WG
17.250	1	BW1 01	Creep	NBG-18	2.56	8.85	WG
16.250	1	EW01 02	Creep	IG-110	2.79	9.70	WG
15.250	1	FW01 01	Creep	IG-430	3.01	10.41	WG
14.250	1	DW1 02	Creep	PCEA	3.22	11.09	WG
13.625	1	TW6601	PB	2114	0.00	7.87	WG
13.000	1	BW1 02	Creep	NBG-18	3.46	11.80	WG
12.000	1	FW01 02	Creep	IG-430	3.64	12.42	WG
11.000	1	EW01 04	Creep	IG-110	3.80	13.01	WG
10.000	1	DW10 01	Creep	PCEA	3.94	13.57	WG
9.000	1	BW1 03	Creep	NBG-18	4.07	14.01	WG
8.000	1	FW01 03	Creep	IG-430	4.19	14.42	WG
7.375	1	FW2102	PB	IG-430	0.00	10.47	WG
6.750	1	TW6003	Creep	2114	0.00	10.47	WG
5.750	1	EW02 01	Creep	IG-110	4.40	15.05	WG
4.750	1	DW10 02	Creep	PCEA	4.47	15.33	WG
3.750	1	BW10 01	Creep	NBG-18	4.52	15.63	WG
2.750	1	FW01 04	Creep	IG-430	4.57	15.70	WG
2.125	1	AP7401	PB	NBG-17	0.00	11.26	AG
1.500	1	AW1 01	Creep	NBG-17	4.61	15.94	WG
Core Center Line							
-2.125	1	AW7301	PB	NBG-17	0.00	11.28	WG
-2.375	1	FW2103	PB	IG-430	0.00	11.28	WG
-2.625	1	DW8009	PB	PCEA	0.00	11.31	WG
-2.875	1	DW8102	PB	PCEA	0.00	11.31	WG
-3.125	1	EA7603	PB	IG-110	0.00	11.31	AG
-3.750	1	PCAN 1	CAN	NBG-17	0.00	11.19	AG
-3.750	1	AP-1P	Pencil	NBG-17	0.00	11.19	AG

Stack 1							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-3.750	1	AP-2P	Pencil	NBG-17	0.00	11.19	AG
-3.750	1	AP-3P	Pencil	NBG-17	0.00	11.19	AG
-4.750	1	PCAN 2	CAN	NBG-18	0.00	11.07	WG
-4.750	1	BW-1P	Pencil	NBG-18	0.00	11.07	WG
-4.750	1	BW-2P	Pencil	NBG-18	0.00	11.07	WG
-4.750	1	BW-3P	Pencil	NBG-18	0.00	11.07	WG
-5.750	1	EW04 02	Creep	IG-110	2.40	13.34	WG
-6.750	1	PCAN 3	CAN	IG-430	0.00	10.73	WG
-6.750	1	FW-1P	Pencil	IG-430	0.00	10.73	WG
-6.750	1	FW-2P	Pencil	IG-430	0.00	10.73	WG
-6.750	1	FW-3P	Pencil	IG-430	0.00	10.73	WG
-7.750	1	DA2 02	Creep	PCEA	2.94	13.57	AG
-8.375	1	TW6602	PB	2114	0.00	10.63	WG
-9.000	1	FW02 02	Creep	IG-430	4.32	14.75	WG
-10.000	1	BW10 03	Creep	NBG-18	4.23	14.40	WG
-11.000	1	DW10 04	Creep	PCEA	4.12	14.01	WG
-12.000	1	FW10 02	Creep	IG-430	2.71	12.29	WG
-13.000	1	FW02 03	Creep	IG-430	3.87	13.05	WG
-14.000	1	BP3 01	Creep	NBG-18	3.15	11.93	AG
-14.625	1	EW8101	PB	IG-110	0.00	8.38	WG
-15.250	1	DW11 01	Creep	PCEA	3.52	11.90	WG
-16.250	1	AW1 02	Creep	NBG-17	4.63	12.54	WG
-17.250	1	PCAN 4	CAN	NBG-18	0.00	7.42	AG
-17.250	1	BP-1P	Pencil	NBG-18	0.00	7.42	AG
-17.250	1	BP-2P	Pencil	NBG-18	0.00	7.42	AG
-17.250	1	BP-3P	Pencil	NBG-18	0.00	7.42	AG
-18.250	1	PCAN 5	CAN	NBG-17	0.00	6.84	AG
-18.250	1	AP-4P	Pencil	NBG-17	0.00	6.84	AG
-18.250	1	AP-5P	Pencil	NBG-17	0.00	6.84	AG
-18.250	1	AP-6P	Pencil	NBG-17	0.00	6.84	AG
-19.250	1	PCAN 6	CAN	NBG-18	0.00	6.22	AG
-19.250	1	BP-4P	Pencil	NBG-18	0.00	6.22	AG
-19.250	1	BP-5P	Pencil	NBG-18	0.00	6.22	AG
-19.250	1	BP-6P	Pencil	NBG-18	0.00	6.22	AG
-19.875	1	DA6201	PB	PCEA	0.00	5.62	AG
-20.500	1	PCAN 7	CAN	PCEA	0.00	5.02	AG
-20.500	1	DA-1P	Pencil	PCEA	0.00	5.02	AG

Stack 1							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-20.500	1	DA-2P	Pencil	PCEA	0.00	5.02	AG
-20.500	1	DA-3P	Pencil	PCEA	0.00	5.02	AG
-21.125	1	BP7 06	PB	NBG-18	2.24	7.26	AG
-21.375	1	AW7302	PB	NBG-17	0.00	5.02	WG
-21.625	1	AP7402	PB	NBG-17	0.00	4.43	AG
-21.875	1	EA7601	PB	IG-110	0.00	4.43	AG
-22.125	1	DW18 03	PB	PCEA	1.98	6.40	WG
-22.375	1	AW7303	PB	NBG-17	0.00	4.43	WG
-22.625	1	AP7403	PB	NBG-17	0.00	3.69	AG
-22.875	1	FW15 01	PB	IG-430	1.77	5.46	WG
-23.125	1	EW14 01	PB	IG-110	1.70	5.39	WG
-23.375	1	TP18	PB	2114	1.42	5.11	AG

Stack 2							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
20.125	2	M2-02	PB	NBG-25	0.00	4.39	AG
19.500	2	EW03 01	Creep	IG-110	2.04	7.08	WG
18.875	2	FW2104	PB	IG-430	0.00	5.04	WG
18.250	2	FW03 01	Creep	IG-430	2.35	8.03	WG
17.250	2	DA4 02	Creep	PCEA	2.59	8.93	AG
16.250	2	BP4 02	Creep	NBG-18	2.82	9.72	AG
15.250	2	AW1 03	Creep	NBG-17	3.04	10.51	WG
14.250	2	EW03 02	Creep	IG-110	3.25	11.15	WG
13.625	2	TW6603	PB	2114	0.00	7.90	WG
13.000	2	DW11 03	Creep	PCEA	3.49	11.88	WG
12.000	2	BW11 03	Creep	NBG-18	3.66	12.53	WG
11.000	2	TW5503	Creep	2114	0.00	9.26	WG
10.000	2	AW10 01	Creep	NBG-17	3.97	13.61	WG
9.000	2	EW03 03	Creep	IG-110	4.10	14.16	WG
8.000	2	DA4 03	Creep	PCEA	4.21	14.51	AG
7.375	2	FW2105	PB	IG-430	0.00	10.53	WG
6.750	2	BP4 03	Creep	NBG-18	4.34	14.87	AG
5.750	2	FW03 02	Creep	IG-430	4.43	15.17	WG
4.750	2	AP4 02	Creep	NBG-17	4.50	15.50	AG
3.750	2	TW5603	Creep	2114	0.00	11.19	WG
2.750	2	DW11 04	Creep	PCEA	4.60	15.88	WG

Stack 2							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
2.125	2	AP7405	PB	NBG-17	0.00	11.35	AG
1.500	2	BW12 01	Creep	NBG-18	4.64	16.08	WG
Core Center Line							
-2.500	2	BW12 02	Creep	NBG-18	4.66	16.07	WG
-3.125	2	EW8206	PB	IG-110	0.00	11.41	WG
-3.750	2	DW12 01	Creep	PCEA	4.64	15.92	WG
-4.750	2	PCAN 8	CAN	IG-110	0.00	11.23	WG
-4.750	2	EW-1P	Pencil	IG-110	0.00	11.23	WG
-4.750	2	EW-2P	Pencil	IG-110	0.00	11.23	WG
-4.750	2	EW-3P	Pencil	IG-110	0.00	11.23	WG
-5.750	2	AP4 03	Creep	NBG-17	4.57	15.62	AG
-6.750	2	FW03 03	Creep	IG-430	4.51	15.42	WG
-7.750	2	BP5 01	Creep	NBG-18	4.45	15.16	AG
-8.375	2	BP5501	PB	NBG-18	0.00	10.71	AG
-9.000	2	DA5 01	Creep	PCEA	4.35	14.87	AG
-10.000	2	EW03 04	Creep	IG-110	4.25	14.49	WG
-11.000	2	AW10 02	Creep	NBG-17	4.15	14.14	WG
-12.000	2	PCAN 9	CAN	NBG-17	0.00	9.62	AG
-12.000	2	AP-7P	Pencil	NBG-17	0.00	9.62	AG
-12.000	2	AP-8P	Pencil	NBG-17	0.00	9.62	AG
-12.000	2	AP-9P	Pencil	NBG-17	0.00	9.62	AG
-13.000	2	BW12 03	Creep	NBG-18	3.89	13.13	WG
-14.000	2	DW12 02	Creep	PCEA	3.74	12.58	WG
-14.625	2	BW6601	PB	NBG-18	0.00	8.45	WG
-15.250	2	PCAN 10	CAN	IG-110	0.00	8.45	WG
-15.250	2	EW-4P	Pencil	IG-110	0.00	8.45	WG
-15.250	2	EW-5P	Pencil	IG-110	0.00	8.45	WG
-15.250	2	EW-6P	Pencil	IG-110	0.00	8.45	WG
-16.250	2	AW10 03	Creep	NBG-17	3.35	11.32	WG
-16.875	2	AW7305	PB	NBG-17	0.00	7.42	WG
-17.125	2	AW7306	PB	NBG-17	0.00	7.42	WG
-17.375	2	BW6602	PB	NBG-18	0.00	7.42	WG
-17.625	2	BW6603	PB	NBG-18	0.00	6.85	WG
-18.250	2	PCAN 11	CAN	PCEA	0.00	6.85	AG
-18.250	2	DA-4P	Pencil	PCEA	0.00	6.85	AG
-18.250	2	DA-5P	Pencil	PCEA	0.00	6.85	AG
-18.250	2	DA-6P	Pencil	PCEA	0.00	6.85	AG

Stack 2							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-19.250	2	TW5204	Creep	2114	0.00	6.27	WG
-19.875	2	EA7604	PB	IG-110	0.00	5.64	AG
-20.500	2	PCAN 12	CAN	IG-110	0.00	5.06	AG
-20.500	2	EA-1P	Pencil	IG-110	0.00	5.06	AG
-20.500	2	EA-2P	Pencil	IG-110	0.00	5.06	AG
-20.500	2	EA-3P	Pencil	IG-110	0.00	5.06	AG
-21.125	2	EA7605	PB	IG-110	0.00	5.06	AG
-21.375	2	BW6604	PB	NBG-18	0.00	5.06	WG
-21.625	2	BP5502	PB	NBG-18	0.00	4.41	AG
-21.875	2	TP19	PB	2114	2.04	6.45	AG
-22.125	2	FW2106	PB	IG-430	0.00	4.41	WG
-22.375	2	BW6605	PB	NBG-18	0.00	4.41	WG
-22.625	2	BP5503	PB	NBG-18	0.00	3.72	AG
-22.875	2	EA7606	PB	IG-110	0.00	3.72	AG
-23.125	2	BW6606	PB	NBG-18	0.00	3.72	WG
-23.375	2	FW15 02	PB	IG-430	1.49	5.21	WG

Stack 3							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
20.125	3	M2-03	PB	NBG-25	0.00	4.39	AG
19.500	3	TW5502	Creep	2114	0.00	4.96	WG
18.875	3	TW6604	PB	2114	0.00	4.96	WG
18.250	3	DW12 03	Creep	PCEA	2.33	8.01	WG
17.250	3	BW13 01	Creep	NBG-18	2.56	8.86	WG
16.250	3	EW04 03	Creep	IG-110	2.79	9.64	WG
15.250	3	FW04 01	Creep	IG-430	3.00	10.39	WG
14.250	3	DW12 04	Creep	PCEA	3.20	11.05	WG
13.625	3	FW2109	PB	IG-430	0.00	7.85	WG
13.000	3	BW13 02	Creep	NBG-18	3.43	11.75	WG
12.000	3	FW04 02	Creep	IG-430	3.61	12.32	WG
11.000	3	EW04 04	Creep	IG-110	3.76	12.98	WG
10.000	3	DW13 01	Creep	PCEA	3.90	13.49	WG
9.000	3	BW13 03	Creep	NBG-18	4.03	13.96	WG
8.000	3	FW04 04	Creep	IG-430	4.14	14.29	WG
7.375	3	BP5505	PB	NBG-18	0.00	10.42	AG
6.750	3	TW5602	Creep	2114	0.00	10.42	WG

Stack 3							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
5.750	3	EW05 01	Creep	IG-110	4.35	15.01	WG
4.750	3	DW13 02	Creep	PCEA	4.42	15.29	WG
3.750	3	BW14 01	Creep	NBG-18	4.47	15.53	WG
2.750	3	FW05 01	Creep	IG-430	4.52	15.64	WG
2.125	3	FW2110	PB	IG-430	0.00	11.23	WG
1.500	3	AW11 01	Creep	NBG-17	4.56	15.83	WG
Core Center Line							
-2.500	3	AW11 02	Creep	NBG-17	4.58	15.84	WG
-3.125	3	AW7307	PB	NBG-17	0.00	11.26	WG
-3.375	3	EA7607	PB	IG-110	0.00	11.26	AG
-3.625	3	EA7608	PB	IG-110	0.00	11.17	AG
-3.875	3	HOPG 1	PB	HOPG	0.00	11.17	AG
-4.125	3	FW2111	PB	IG-430	0.00	11.17	WG
-4.375	3	BP5506	PB	NBG-18	0.00	11.17	AG
-4.625	3	BP5507	PB	NBG-18	0.00	11.11	AG
-4.875	3	DA6202	PB	PCEA	0.00	11.11	AG
-5.125	3	DA6203	PB	PCEA	0.00	11.11	AG
-5.750	3	PCAN 13	CAN	PCEA	0.00	10.90	AG
-5.750	3	DA-7P	Pencil	PCEA	0.00	10.90	AG
-5.750	3	DA-8P	Pencil	PCEA	0.00	10.90	AG
-5.750	3	DA-9P	Pencil	PCEA	0.00	10.90	AG
-6.750	3	PCAN 14	CAN	IG-430	0.00	10.77	WG
-6.750	3	FW-4P	Pencil	IG-430	0.00	10.77	WG
-6.750	3	FW-5P	Pencil	IG-430	0.00	10.77	WG
-6.750	3	FW-6P	Pencil	IG-430	0.00	10.77	WG
-7.750	3	PCAN 15	CAN	PCEA	0.00	10.60	WG
-7.750	3	DW-1P	Pencil	PCEA	0.00	10.60	WG
-7.750	3	DW-2P	Pencil	PCEA	0.00	10.60	WG
-7.750	3	DW-3P	Pencil	PCEA	0.00	10.60	WG
-8.375	3	DW8001	PB	PCEA	0.00	10.60	WG
-9.000	3	FW05 03	Creep	IG-430	4.27	14.69	WG
-10.000	3	BW14 03	Creep	NBG-18	4.17	14.30	WG
-11.000	3	DW13 04	Creep	PCEA	4.07	13.95	WG
-12.000	3	PCAN 16	CAN	NBG-18	0.00	9.44	WG
-12.000	3	BW-4P	Pencil	NBG-18	0.00	9.44	WG
-12.000	3	BW-5P	Pencil	NBG-18	0.00	9.44	WG
-12.000	3	BW-6P	Pencil	NBG-18	0.00	9.44	WG

Stack 3							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-13.000	3	FW05 04	Creep	IG-430	3.82	12.95	WG
-14.000	3	PCAN 17	CAN	NBG-18	0.00	8.75	AG
-14.000	3	BP-7P	Pencil	NBG-18	0.00	8.75	AG
-14.000	3	BP-8P	Pencil	NBG-18	0.00	8.75	AG
-14.000	3	BP-9P	Pencil	NBG-18	0.00	8.75	AG
-14.625	3	HOPG 2	PB	HOPG	0.00	8.33	AG
-15.250	3	DW14 01	Creep	PCEA	3.47	11.80	WG
-16.250	3	PCAN 18	CAN	PCEA	0.00	7.86	AG
-16.250	3	DA-10P	Pencil	PCEA	0.00	7.86	AG
-16.250	3	DA-11P	Pencil	PCEA	0.00	7.86	AG
-16.250	3	DA-12P	Pencil	PCEA	0.00	7.86	AG
-16.875	3	EA7609	PB	IG-110	0.00	7.41	AG
-17.125	3	EA7610	PB	IG-110	0.00	7.41	AG
-17.375	3	EW8102	PB	IG-110	0.00	7.41	WG
-17.625	3	DA6204	PB	PCEA	0.00	6.82	AG
-18.250	3	PCAN 19	CAN	IG-430	0.00	6.82	WG
-18.250	3	FW-7P	Pencil	IG-430	0.00	6.82	WG
-18.250	3	FW-8P	Pencil	IG-430	0.00	6.82	WG
-18.250	3	FW-9P	Pencil	IG-430	0.00	6.82	WG
-19.250	3	TW5104	Creep	2114	0.00	6.21	WG
-19.875	3	BW6607	PB	NBG-18	0.00	5.63	WG
-20.125	3	EW8103	PB	IG-110	0.00	5.63	WG
-20.375	3	EW8104	PB	IG-110	0.00	5.63	WG
-20.625	3	AP7406	PB	NBG-17	0.00	5.01	AG
-20.875	3	AP7407	PB	NBG-17	0.00	5.01	AG
-21.125	3	FW2112	PB	IG-430	0.00	5.01	WG
-21.375	3	DW8103	PB	PCEA	0.00	5.01	WG
-21.625	3	DA6205	PB	PCEA	0.00	4.37	AG
-21.875	3	EW8105	PB	IG-110	0.00	4.37	WG
-22.125	3	EW8106	PB	IG-110	0.00	4.37	WG
-22.375	3	DW8104	PB	PCEA	0.00	4.37	WG
-22.625	3	DA6206	PB	PCEA	0.00	3.68	AG
-22.875	3	FW2113	PB	IG-430	0.00	3.68	WG
-23.125	3	TP20	PB	2114	1.68	5.36	AG
-23.375	3	DW8005	PB	PCEA	0.00	3.68	WG

Stack 4							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
20.125	4	M2-04	PB	NBG-25	0	4.32	AG
19.500	4	EW06 01	Creep	IG-110	1.98	6.94	WG
18.875	4	TW6605	PB	2114	0.00	4.96	WG
18.250	4	FW06 02	Creep	IG-430	2.27	7.84	WG
17.250	4	DA5 03	Creep	PCEA	2.51	8.70	AG
16.250	4	BP5 03	Creep	NBG-18	2.73	9.52	AG
15.250	4	AW11 03	Creep	NBG-17	2.94	10.26	WG
14.250	4	EW06 02	Creep	IG-110	3.14	10.86	WG
13.625	4	FW2116	PB	IG-430	0.00	7.72	WG
13.000	4	DW14 03	Creep	PCEA	3.36	11.53	WG
12.000	4	BW15 03	Creep	NBG-18	3.53	12.15	WG
11.000	4	TW5301	Creep	2114	0.00	9.10	WG
10.000	4	AW12 01	Creep	NBG-17	3.82	13.24	WG
9.000	4	EW06 03	Creep	IG-110	3.95	13.69	WG
8.000	4	DA6 01	Creep	PCEA	4.06	14.06	AG
7.375	4	BP5508	PB	NBG-18	0.00	10.21	AG
6.750	4	BP6 01	Creep	NBG-18	4.18	14.38	AG
5.750	4	FW06 03	Creep	IG-430	4.26	14.77	WG
4.750	4	AP5 01	Creep	NBG-17	4.32	15.01	AG
3.750	4	TW5701	Creep	2114	0.00	10.82	WG
2.750	4	DW14 04	Creep	PCEA	4.42	15.40	WG
2.125	4	FW2117	PB	IG-430	0.00	11.09	WG
1.500	4	BW16 01	Creep	NBG-18	4.46	15.56	WG
Core Center Line							
-2.500	4	BW16 02	Creep	NBG-18	4.48	15.48	WG
-3.125	4	TW6606	PB	2114	0.00	11.00	WG
-3.750	4	DW15 02	Creep	PCEA	4.46	15.40	WG
-4.750	4	PCAN 20	CAN	2114	0.00	10.92	AG
-4.750	4	TA-1P	Pencil	2114	0.00	10.92	AG
-4.750	4	TA-2P	Pencil	2114	0.00	10.92	AG
-4.750	4	TA-3P	Pencil	2114	0.00	10.92	AG
-5.750	4	AP5 02	Creep	NBG-17	4.39	15.11	AG
-6.750	4	FW06 04	Creep	IG-430	4.34	14.93	WG
-7.750	4	BP6 02	Creep	NBG-18	4.27	14.65	AG
-8.375	4	EW8107	PB	IG-110	0.00	10.38	WG
-9.000	4	DA6 02	Creep	PCEA	4.18	14.44	AG
-10.000	4	EW06 04	Creep	IG-110	4.09	14.07	WG

Stack 4							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-11.000	4	AW12 02	Creep	NBG-17	3.99	13.65	WG
-12.000	4	FW03 04	Creep	IG-430	2.70	12.07	WG
-13.000	4	BW16 03	Creep	NBG-18	3.75	12.76	WG
-14.000	4	DW15 03	Creep	PCEA	3.60	12.22	WG
-14.625	4	BP5509	PB	NBG-18	0.00	8.23	AG
-15.250	4	EW07 01	Creep	IG-110	3.41	11.64	WG
-16.250	4	AW13 02	Creep	NBG-17	4.59	12.33	WG
-17.250	4	BP6 03	Creep	NBG-18	3.04	10.31	AG
-18.250	4	DA7 01	Creep	PCEA	2.84	9.58	AG
-19.250	4	FW07 01	Creep	IG-430	2.62	8.77	WG
-19.875	4	FW2118	PB	IG-430	0.00	5.54	WG
-20.125	4	AW7308	PB	NBG-17	0.00	5.54	WG
-20.375	4	AW7309	PB	NBG-17	0.00	5.54	WG
-20.625	4	BW6608	PB	NBG-18	0.00	4.95	WG
-20.875	4	BW6609	PB	NBG-18	0.00	4.95	WG
-21.125	4	EW8108	PB	IG-110	0.00	4.95	WG
-21.375	4	AW7310	PB	NBG-17	0.00	4.95	WG
-21.625	4	AP7408	PB	NBG-17	0.00	4.33	AG
-21.875	4	EA7611	PB	IG-110	0.00	4.33	AG
-22.125	4	DW18 06	PB	PCEA	1.92	6.25	WG
-22.375	4	AW7311	PB	NBG-17	0.00	4.33	WG
-22.625	4	AP7409	PB	NBG-17	0.00	3.66	AG
-22.875	4	FW2119	PB	IG-430	0.00	3.66	WG
-23.125	4	EA7701	PB	IG-110	0.00	3.66	AG
-23.375	4	TP21	PB	2114	1.38	5.05	AG

Stack 5							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
20.125	5	M2-05	PB	NBG-25	0.00	4.36	AG
19.500	5	TW5002	Creep	2114	0.00	4.99	WG
18.875	5	TW6607	PB	2114	0.00	4.99	WG
18.250	5	DW15 04	Creep	PCEA	2.35	8.00	WG
17.250	5	BW2 01	Creep	NBG-18	2.58	8.87	WG
16.250	5	EW07 03	Creep	IG-110	2.81	9.70	WG
15.250	5	FW07 03	Creep	IG-430	3.02	10.46	WG
14.250	5	DW16 01	Creep	PCEA	3.22	11.13	WG

Stack 5							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
13.625	5	FW2120	PB	IG-430	0.00	7.91	WG
13.000	5	BW2 02	Creep	NBG-18	3.46	11.86	WG
12.000	5	FW07 04	Creep	IG-430	3.63	12.45	WG
11.000	5	EW07 04	Creep	IG-110	3.78	13.02	WG
10.000	5	DW16 02	Creep	PCEA	3.93	13.51	WG
9.000	5	BW2 03	Creep	NBG-18	4.05	13.96	WG
8.000	5	FW08 01	Creep	IG-430	4.17	14.36	WG
7.375	5	BP5510	PB	NBG-18	0.00	10.48	AG
6.750	5	TW5201	Creep	2114	0.00	10.48	WG
5.750	5	EW08 01	Creep	IG-110	4.37	15.03	WG
4.750	5	DW16 03	Creep	PCEA	4.44	15.37	WG
3.750	5	BW3 01	Creep	NBG-18	4.49	15.57	WG
2.750	5	FW08 02	Creep	IG-430	4.54	15.74	WG
2.125	5	FW2121	PB	IG-430	0.00	11.28	WG
1.500	5	AW13 01	Creep	NBG-17	4.57	15.88	WG
Core Center Line							
-2.125	5	DW8006	PB	PCEA	0.00	11.33	WG
-2.375	5	DW8101	PB	PCEA	0.00	11.33	WG
-2.625	5	FW2122	PB	IG-430	0.00	11.31	WG
-2.875	5	EW8207	PB	IG-110	0.00	11.31	WG
-3.125	5	FW2123	PB	IG-430	0.00	11.31	WG
-3.750	5	PCAN 21	CAN	PCEA	0.00	11.21	WG
-3.750	5	DW-4P	Pencil	PCEA	0.00	11.21	WG
-3.750	5	DW-5P	Pencil	PCEA	0.00	11.21	WG
-3.750	5	DW-6P	Pencil	PCEA	0.00	11.21	WG
-4.375	5	TW6608	PB	2114	0.00	11.21	WG
-4.625	5	EW8109	PB	IG-110	0.00	11.08	WG
-4.875	5	AP7411	PB	NBG-17	0.00	11.08	AG
-5.125	5	AP7412	PB	NBG-17	0.00	11.08	AG
-5.750	5	EW07 02	Creep	IG-110	2.33	13.28	WG
-6.750	5	PCAN 22	CAN	NBG-17	0.00	10.83	WG
-6.750	5	AW-1P	Pencil	NBG-17	0.00	10.83	WG
-6.750	5	AW-2P	Pencil	NBG-17	0.00	10.83	WG
-6.750	5	AW-3P	Pencil	NBG-17	0.00	10.83	WG
-7.750	5	DA5 02	Creep	PCEA	2.93	13.55	AG
-8.375	5	DW8010	PB	PCEA	0.00	10.62	WG
-9.000	5	FW08 04	Creep	IG-430	4.28	14.66	WG

Stack 5							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-10.000	5	BW3 03	Creep	NBG-18	4.19	14.42	WG
-11.000	5	DW17 01	Creep	PCEA	4.08	13.97	WG
-12.000	5	PCAN 23	CAN	NBG-17	0.00	9.54	WG
-12.000	5	AW-4P	Pencil	NBG-17	0.00	9.54	WG
-12.000	5	AW-5P	Pencil	NBG-17	0.00	9.54	WG
-12.000	5	AW-6P	Pencil	NBG-17	0.00	9.54	WG
-13.000	5	FW09 01	Creep	IG-430	3.83	12.96	WG
-14.000	5	BP5 02	Creep	NBG-18	3.15	11.91	AG
-14.625	5	BP5511	PB	NBG-18	0.00	8.31	AG
-15.250	5	DW17 02	Creep	PCEA	3.48	11.79	WG
-16.250	5	PCAN 24	CAN	NBG-17	0.00	7.90	AG
-16.250	5	AP-10P	Pencil	NBG-17	0.00	7.90	AG
-16.250	5	AP-11P	Pencil	NBG-17	0.00	7.90	AG
-16.250	5	AP-12P	Pencil	NBG-17	0.00	7.90	AG
-16.875	5	TW6609	PB	2114	0.00	7.44	WG
-17.125	5	FW2124	PB	IG-430	0.00	7.44	WG
-17.375	5	AP7501	PB	NBG-17	0.00	7.44	AG
-17.625	5	AP7502	PB	NBG-17	0.00	6.84	AG
-18.250	5	PCAN 25	CAN	IG-110	0.00	6.84	AG
-18.250	5	EA-4P	Pencil	IG-110	0.00	6.84	AG
-18.250	5	EA-5P	Pencil	IG-110	0.00	6.84	AG
-18.250	5	EA-6P	Pencil	IG-110	0.00	6.84	AG
-19.250	5	PCAN 26	CAN	IG-430	0.00	6.23	WG
-19.250	5	FW-10P	Pencil	IG-430	0.00	6.23	WG
-19.250	5	FW-11P	Pencil	IG-430	0.00	6.23	WG
-19.250	5	FW-12P	Pencil	IG-430	0.00	6.23	WG
-19.875	5	AW7501	PB	NBG-17	0.00	5.62	WG
-20.125	5	DW8002	PB	PCEA	0.00	5.62	WG
-20.375	5	DW8004	PB	PCEA	0.00	5.62	WG
-20.625	5	FW2125	PB	IG-430	0.00	5.03	WG
-20.875	5	FW2126	PB	IG-430	0.00	5.03	WG
-21.125	5	DA6208	PB	PCEA	0.00	5.03	AG
-21.375	5	BW6610	PB	NBG-18	0.00	5.03	WG
-21.625	5	BP5512	PB	NBG-18	0.00	4.39	AG
-21.875	5	TP22	PB	2114	2.02	6.41	AG
-22.125	5	FW2127	PB	IG-430	0.00	4.39	WG
-22.375	5	BW6706	PB	NBG-18	0.00	4.39	WG

Stack 5							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-22.625	5	BP5513	PB	NBG-18	0.00	3.70	AG
-22.875	5	FW2128	PB	IG-430	0.00	3.70	WG
-23.125	5	TW6610	PB	2114	0.00	3.70	WG
-23.375	5	BP5514	PB	NBG-18	0.00	3.70	AG

Stack 6							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
20.125	6	M2-06	PB	NBG-25	0.00	4.38	AG
19.500	6	EW09 01	Creep	IG-110	2.05	7.08	WG
18.875	6	FW2130	PB	IG-430	0.00	5.02	WG
18.250	6	FW09 03	Creep	IG-430	2.36	8.07	WG
17.250	6	DA3 03	Creep	PCEA	2.60	8.96	AG
16.250	6	BP4 01	Creep	NBG-18	2.83	9.79	AG
15.250	6	AW13 03	Creep	NBG-17	3.05	10.49	WG
14.250	6	EW09 02	Creep	IG-110	3.25	11.14	WG
13.625	6	TW6611	PB	2114	0.00	7.89	WG
13.000	6	DW2 01	Creep	PCEA	3.49	11.91	WG
12.000	6	BW4 03	Creep	NBG-18	3.67	12.49	WG
11.000	6	TW5702	Creep	2114	0.00	9.30	WG
10.000	6	AW14 01	Creep	NBG-17	3.97	13.65	WG
9.000	6	EA9 02	Creep	IG-110	4.10	14.05	AG
8.000	6	DA3 02	Creep	PCEA	4.21	14.45	AG
7.375	6	FW2131	PB	IG-430	0.00	10.52	WG
6.750	6	BP3 03	Creep	NBG-18	4.34	14.85	AG
5.750	6	FW09 04	Creep	IG-430	4.42	15.22	WG
4.750	6	AP5 03	Creep	NBG-17	4.49	15.50	AG
3.750	6	TW5601	Creep	2114	0.00	11.17	WG
2.750	6	DW2 02	Creep	PCEA	4.60	15.95	WG
2.125	6	AP7503	PB	NBG-17	0.00	11.34	AG
1.500	6	BW5 01	Creep	NBG-18	4.64	16.07	WG
Core Center Line							
-2.500	6	BW5 02	Creep	NBG-18	4.66	16.06	WG
-3.125	6	AP7505	PB	NBG-17	0.00	11.40	AG
-3.750	6	DW2 03	Creep	PCEA	4.64	15.92	WG
-4.750	6	PCAN 27	CAN	IG-110	0.00	11.16	AG
-4.750	6	EA-7P	Pencil	IG-110	0.00	11.16	AG

Stack 6							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-4.750	6	EA-8P	Pencil	IG-110	0.00	11.16	AG
-4.750	6	EA-9P	Pencil	IG-110	0.00	11.16	AG
-5.750	6	AP6 01	Creep	NBG-17	4.57	15.64	AG
-6.750	6	FW10 01	Creep	IG-430	4.51	15.43	WG
-7.750	6	BP3 02	Creep	NBG-18	4.45	15.18	AG
-8.375	6	BW6712	PB	NBG-18	0.00	10.73	WG
-9.000	6	DA2 03	Creep	PCEA	4.35	14.92	AG
-10.000	6	EW09 04	Creep	IG-110	4.25	14.53	WG
-11.000	6	AW14 02	Creep	NBG-17	4.15	14.11	WG
-12.000	6	PCAN 28	CAN	IG-110	0.00	9.60	WG
-12.000	6	EW-7P	Pencil	IG-110	0.00	9.60	WG
-12.000	6	EW-8P	Pencil	IG-110	0.00	9.60	WG
-12.000	6	EW-9P	Pencil	IG-110	0.00	9.60	WG
-13.000	6	BW5 03	Creep	NBG-18	3.89	13.11	WG
-14.000	6	DW2 04	Creep	PCEA	3.74	12.55	WG
-14.625	6	BW6615	PB	NBG-18	0.00	8.39	WG
-15.250	6	EW10 01	Creep	IG-110	3.54	11.93	WG
-16.250	6	AW14 03	Creep	NBG-17	3.35	11.33	WG
-16.875	6	DW8007	PB	PCEA	0.00	7.49	WG
-17.125	6	DW8008	PB	PCEA	0.00	7.49	WG
-17.375	6	HOPG 3	PB	HOPG	0.00	7.49	AG
-17.625	6	FW2132	PB	IG-430	0.00	6.87	WG
-17.875	6	BP5515	PB	NBG-18	0.00	6.87	AG
-18.125	6	BP5516	PB	NBG-18	0.00	6.87	AG
-18.375	6	DA6214	PB	PCEA	0.00	6.87	AG
-18.625	6	DA6302	PB	PCEA	0.00	6.28	AG
-19.250	6	TW5302	Creep	2114	0.00	6.28	WG
-19.875	6	DW8011	PB	PCEA	0.00	5.67	WG
-20.125	6	BP5520	PB	NBG-18	0.00	5.67	AG
-20.375	6	BP5602	PB	NBG-18	0.00	5.67	AG
-20.625	6	DA6210	PB	PCEA	0.00	5.06	AG
-20.875	6	DA6211	PB	PCEA	0.00	5.06	AG
-21.125	6	EA7712	PB	IG-110	0.00	5.06	AG
-21.375	6	DW8012	PB	PCEA	0.00	5.06	WG
-21.625	6	DA6212	PB	PCEA	0.00	4.39	AG
-21.875	6	FW2133	PB	IG-430	0.00	4.39	WG
-22.125	6	DW8003	PB	PCEA	0.00	4.39	WG

Stack 6							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-22.375	6	DW8111	PB	PCEA	0.00	4.39	WG
-22.625	6	DA6213	PB	PCEA	0.00	3.71	AG
-22.875	6	TW6612	PB	2114	0.00	3.71	WG
-23.125	6	TP23	PB	2114	1.71	5.41	AG
-23.375	6	DW8302	PB	PCEA	0.00	3.71	WG

Stack 7							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
17.375	7	Flux Wire	PB	Flux Wire	0.00	6.31	WG
17.125	7	Flux Wire	PB	Flux Wire	0.00	6.31	WG
16.875	7	EA7806	PB	IG-110	0.00	6.31	AG
16.625	7	TW6701	PB	2114	0.00	6.31	WG
16.375	7	AW7507	PB	NBG-17	0.00	6.89	WG
16.125	7	TP11	PB	2114	2.50	9.39	AG
15.875	7	EA7708	PB	IG-110	0.00	6.89	AG
15.625	7	FW2134	PB	IG-430	0.00	6.89	WG
15.375	7	AW7410	PB	NBG-17	0.00	7.38	WG
15.125	7	FW2135	PB	IG-430	0.00	7.38	WG
14.875	7	BP7 08	PB	NBG-18	2.79	10.17	AG
14.625	7	DW18 08	PB	PCEA	2.85	10.23	WG
14.375	7	BP7 09	PB	NBG-18	2.90	10.77	AG
14.125	7	FW15 04	PB	IG-430	2.95	10.83	WG
13.875	7	EW14 04	PB	IG-110	3.01	10.88	WG
13.625	7	Flux Wire	PB	Flux Wire	0.00	7.87	WG
13.375	7	Flux Wire	PB	Flux Wire	0.00	8.36	WG
13.125	7	AW7612	PB	NBG-17	0.00	8.36	WG
12.875	7	EA7801	PB	IG-110	0.00	8.36	AG
12.625	7	FW2136	PB	IG-430	0.00	8.36	WG
12.375	7	EW8112	PB	IG-110	0.00	8.81	WG
12.125	7	TP10	PB	2114	3.36	12.17	AG
11.875	7	DW8110	PB	PCEA	0.00	8.81	WG
11.625	7	TW6702	PB	2114	0.00	8.81	WG
11.375	7	FW2137	PB	IG-430	0.00	9.20	WG
11.125	7	EW8205	PB	IG-110	0.00	9.20	WG
10.875	7	BP7 10	PB	NBG-18	3.58	12.78	AG
10.625	7	DA8 05	PB	PCEA	3.63	12.83	AG

Stack 7							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
10.375	7	AP7 08	PB	NBG-17	3.67	13.33	AG
10.125	7	FW15 05	PB	IG-430	3.71	13.37	WG
9.875	7	EW15 03	PB	IG-110	3.75	13.41	WG
9.625	7	Flux Wire	PB	Flux Wire	0.00	9.66	WG
9.375	7	Flux Wire	PB	Flux Wire	0.00	9.91	WG
9.125	7	AW7605	PB	NBG-17	0.00	9.91	WG
8.875	7	EA7704	PB	IG-110	0.00	9.91	AG
8.625	7	FW2138	PB	IG-430	0.00	9.91	WG
8.375	7	FW2139	PB	IG-430	0.00	10.16	WG
8.125	7	TP09	PB	2114	4.00	14.16	AG
7.875	7	BW6705	PB	NBG-18	0.00	10.16	WG
7.625	7	FW2140	PB	IG-430	0.00	10.16	WG
7.375	7	EW8201	PB	IG-110	0.00	10.44	WG
7.125	7	AW7604	PB	NBG-17	0.00	10.44	WG
6.875	7	BW17 01	PB	NBG-18	4.15	14.59	WG
6.625	7	DA8 04	PB	PCEA	4.18	14.62	AG
6.375	7	AP7 09	PB	NBG-17	4.20	14.91	AG
6.125	7	FW15 06	PB	IG-430	4.23	14.93	WG
5.875	7	EW15 02	PB	IG-110	4.26	14.96	WG
5.625	7	Flux Wire	PB	Flux Wire	0.00	10.70	WG
5.375	7	Flux Wire	PB	Flux Wire	0.00	10.90	WG
5.125	7	AW7611	PB	NBG-17	0.00	10.90	WG
4.875	7	EA7812	PB	IG-110	0.00	10.90	AG
4.625	7	HOPG 4	PB	HOPG	0.00	10.90	AG
4.375	7	DW8206	PB	PCEA	0.00	11.15	WG
4.125	7	TP08	PB	2114	4.41	15.56	AG
3.875	7	BW6616	PB	NBG-18	0.00	11.15	WG
3.625	7	DA6308	PB	PCEA	0.00	11.15	AG
3.375	7	TW6703	PB	2114	0.00	11.21	WG
3.125	7	BW6620	PB	NBG-18	0.00	11.21	WG
2.875	7	BW17 09	PB	NBG-18	4.49	15.70	WG
2.625	7	DA8 03	PB	PCEA	4.50	15.72	AG
2.375	7	AP7 10	PB	NBG-17	4.52	15.77	AG
2.125	7	Flux Wire	PB	Flux Wire	0.00	11.25	WG
1.875	7	Flux Wire	PB	Flux Wire	0.00	11.25	WG
1.625	7	BP5607	PB	NBG-18	0.00	11.25	AG
1.375	7	DW8207	PB	PCEA	0.00	11.37	WG

Stack 7							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
1.125	7	TP07	PB	2114	4.60	15.97	AG
0.875	7	AW7403	PB	NBG-17	0.00	11.37	WG
0.625	7	EA7702	PB	IG-110	0.00	11.37	AG
0.375	7	EW8211	PB	IG-110	0.00	11.38	WG
0.125	7	FW2141	PB	IG-430	0.00	11.38	WG
Core Center Line							
-0.125	7	BW17 08	PB	NBG-18	4.62	16.00	WG
-0.375	7	DA8 02	PB	PCEA	4.62	16.00	AG
-0.625	7	AW17 01	PB	NBG-17	4.62	15.97	WG
-0.875	7	FW15 12	PB	IG-430	4.62	15.97	WG
-1.125	7	EW14 12	PB	IG-110	4.62	15.96	WG
-1.375	7	Flux Wire	PB	Flux Wire	0.00	11.34	WG
-1.625	7	Flux Wire	PB	Flux Wire	0.00	11.35	WG
-1.875	7	AP7506	PB	NBG-17	0.00	11.35	AG
-2.125	7	EA7805	PB	IG-110	0.00	11.35	AG
-2.375	7	FW2142	PB	IG-430	0.00	11.35	WG
-2.625	7	FW2143	PB	IG-430	0.00	11.31	WG
-2.875	7	TP06	PB	2114	4.60	15.91	AG
-3.125	7	TW6704	PB	2114	0.00	11.31	WG
-3.375	7	EW8202	PB	IG-110	0.00	11.31	WG
-3.625	7	BW6711	PB	NBG-18	0.00	11.31	WG
-3.875	7	AW7601	PB	NBG-17	0.00	11.31	WG
-4.125	7	BW17 07	PB	NBG-18	4.56	15.87	WG
-4.375	7	DA8 01	PB	PCEA	4.55	15.86	AG
-4.625	7	AW17 02	PB	NBG-17	4.54	15.64	WG
-4.875	7	FW15 11	PB	IG-430	4.53	15.62	WG
-5.125	7	EW14 11	PB	IG-110	4.52	15.61	WG
-5.375	7	BP5608	PB	NBG-18	0.00	11.09	AG
-5.625	7	DW8204	PB	PCEA	0.00	11.05	WG
-5.875	7	Flux Wire	PB	Flux Wire	0.00	11.05	WG
-6.125	7	Flux Wire	PB	Flux Wire	0.00	11.05	WG
-6.375	7	FW2144	PB	IG-430	0.00	11.05	WG
-6.625	7	TW6705	PB	2114	0.00	10.80	WG
-6.875	7	TP05	PB	2114	4.41	15.21	AG
-7.125	7	AP7507	PB	NBG-17	0.00	10.80	AG
-7.375	7	TW6706	PB	2114	0.00	10.80	WG
-7.625	7	AP7512	PB	NBG-17	0.00	10.68	AG

Stack 7							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-7.875	7	DA6314	PB	PCEA	0.00	10.68	AG
-8.125	7	BW17 05	PB	NBG-18	4.31	15.00	WG
-8.375	7	DW18 12	PB	PCEA	4.29	14.97	WG
-8.625	7	AW17 03	PB	NBG-17	4.27	14.70	WG
-8.875	7	FW15 10	PB	IG-430	4.24	14.67	WG
-9.125	7	EW14 10	PB	IG-110	4.22	14.65	WG
-9.375	7	Flux Wire	PB	Flux Wire	0.00	10.43	WG
-9.625	7	Flux Wire	PB	Flux Wire	0.00	10.14	WG
-9.875	7	AP7603	PB	NBG-17	0.00	10.14	AG
-10.125	7	EA7803	PB	IG-110	0.00	10.14	AG
-10.375	7	FW2145	PB	IG-430	0.00	10.14	WG
-10.625	7	DA6401	PB	PCEA	0.00	9.90	AG
-10.875	7	TP04	PB	2114	4.03	13.93	AG
-11.125	7	TW6707	PB	2114	0.00	9.90	WG
-11.375	7	Flux Wire	PB	Flux Wire	0.00	9.90	WG
-11.625	7	Flux Wire	PB	Flux Wire	0.00	9.55	WG
-11.875	7	EW8203	PB	IG-110	0.00	9.55	WG
-12.125	7	BW17 04	PB	NBG-18	3.86	13.41	WG
-12.375	7	DW18 11	PB	PCEA	3.83	13.38	WG
-12.625	7	AW17 06	PB	NBG-17	3.79	12.96	WG
-12.875	7	FW15 09	PB	IG-430	3.76	12.93	WG
-13.125	7	EW14 09	PB	IG-110	3.72	12.89	WG
-13.375	7	BP5613	PB	NBG-18	0.00	9.17	AG
-13.625	7	DA6402	PB	PCEA	0.00	8.76	AG
-13.875	7	AP7705	PB	NBG-17	0.00	8.76	AG
-14.125	7	EA7810	PB	IG-110	0.00	8.76	AG
-14.375	7	FW2146	PB	IG-430	0.00	8.76	WG
-14.625	7	FW2147	PB	IG-430	0.00	8.37	WG
-14.875	7	TP03	PB	2114	3.43	11.80	AG
-15.125	7	Flux Wire	PB	Flux Wire	0.00	8.37	WG
-15.375	7	Flux Wire	PB	Flux Wire	0.00	8.37	WG
-15.625	7	AP7708	PB	NBG-17	0.00	7.91	AG
-15.875	7	EW8204	PB	IG-110	0.00	7.91	WG
-16.125	7	BW17 03	PB	NBG-18	3.19	11.10	WG
-16.375	7	DW18 10	PB	PCEA	3.14	11.05	WG
-16.625	7	AW17 05	PB	NBG-17	3.09	10.51	WG
-16.875	7	FW15 08	PB	IG-430	3.04	10.45	WG

Stack 7							
Nominal Height	Stack	ID	Type	Grade	Initial Dose	Projected Dose	Grain Orientation
-17.125	7	EW14 08	PB	IG-110	2.99	10.40	WG
-17.375	7	Flux Wire	PB	Flux Wire	0.00	7.41	WG
-17.625	7	Flux Wire	PB	Flux Wire	0.00	6.82	WG
-17.875	7	AP7710	PB	NBG-17	0.00	6.82	AG
-18.125	7	EA7709	PB	IG-110	0.00	6.82	AG
-18.375	7	FW2148	PB	IG-430	0.00	6.82	WG
-18.625	7	DA6405	PB	PCEA	0.00	6.23	AG
-18.875	7	TP02	PB	2114	2.59	8.83	AG
-19.125	7	BW6619	PB	NBG-18	0.00	6.23	WG
-19.375	7	DW8307	PB	PCEA	0.00	6.23	WG
-19.625	7	FW2149	PB	IG-430	0.00	5.67	WG
-19.875	7	TW6708	PB	2114	0.00	5.67	WG
-20.125	7	BW17 02	PB	NBG-18	2.29	7.96	WG
-20.375	7	DW18 09	PB	PCEA	2.22	7.89	WG
-20.625	7	AW17 04	PB	NBG-17	2.16	7.21	WG
-20.875	7	FW15 07	PB	IG-430	2.10	7.14	WG
-21.125	7	EW14 07	PB	IG-110	2.03	7.07	WG
-21.375	7	Flux Wire	PB	Flux Wire	0.00	5.05	WG
-21.625	7	Flux Wire	PB	Flux Wire	0.00	4.37	WG
-22.250	7	PCAN 29	CAN	IG-430	0.00	4.37	WG
-22.250	7	FW-13P	Pencil	IG-430	0.00	4.37	WG
-22.250	7	FW-14P	Pencil	IG-430	0.00	4.37	WG
-22.250	7	FW-15P	Pencil	IG-430	0.00	4.37	WG
-22.875	7	TP01	PB	2114	1.55	5.25	AG
-23.500	7	PCAN 30	CAN	IG-430	0.00	2.91	WG
-23.5	7	FW-16P	Pencil	IG-430	0.00	2.91	WG
-23.5	7	FW-17P	Pencil	IG-430	0.00	2.91	WG
-23.5	7	FW-18P	Pencil	IG-430	0.00	2.91	WG

Appendix D

Dose Profiles for HDG-1 Specimens

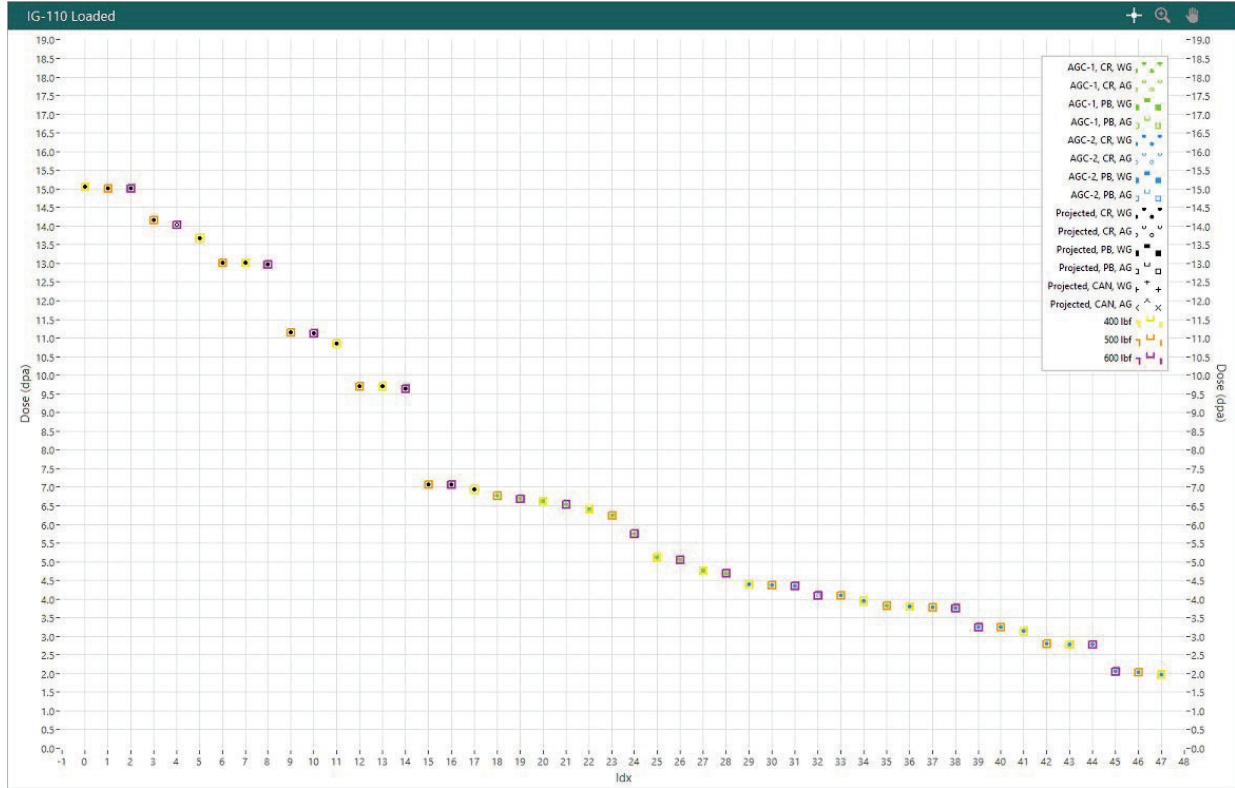


Figure D-1. IG-110 loaded specimens estimated dose profile for HDG-1.

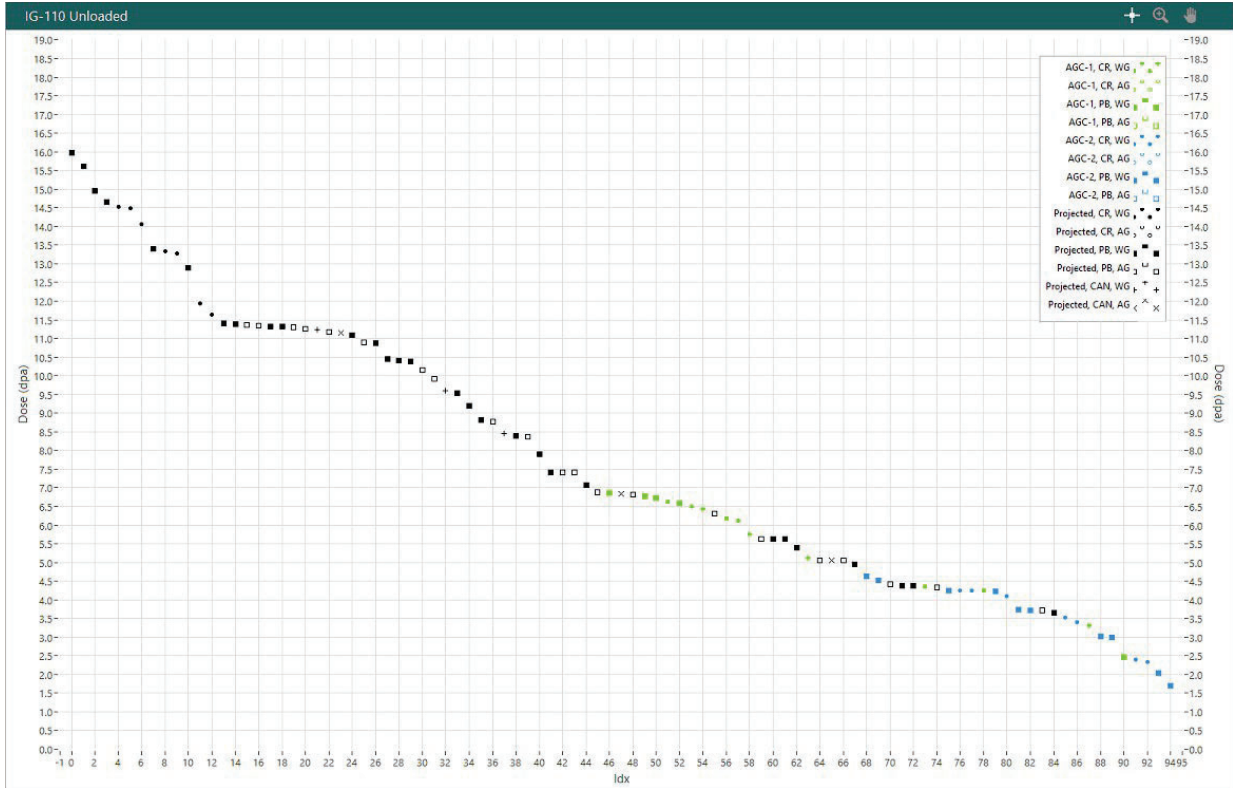


Figure D-2. IG-110 unloaded specimens estimated dose profile for HDG-1.

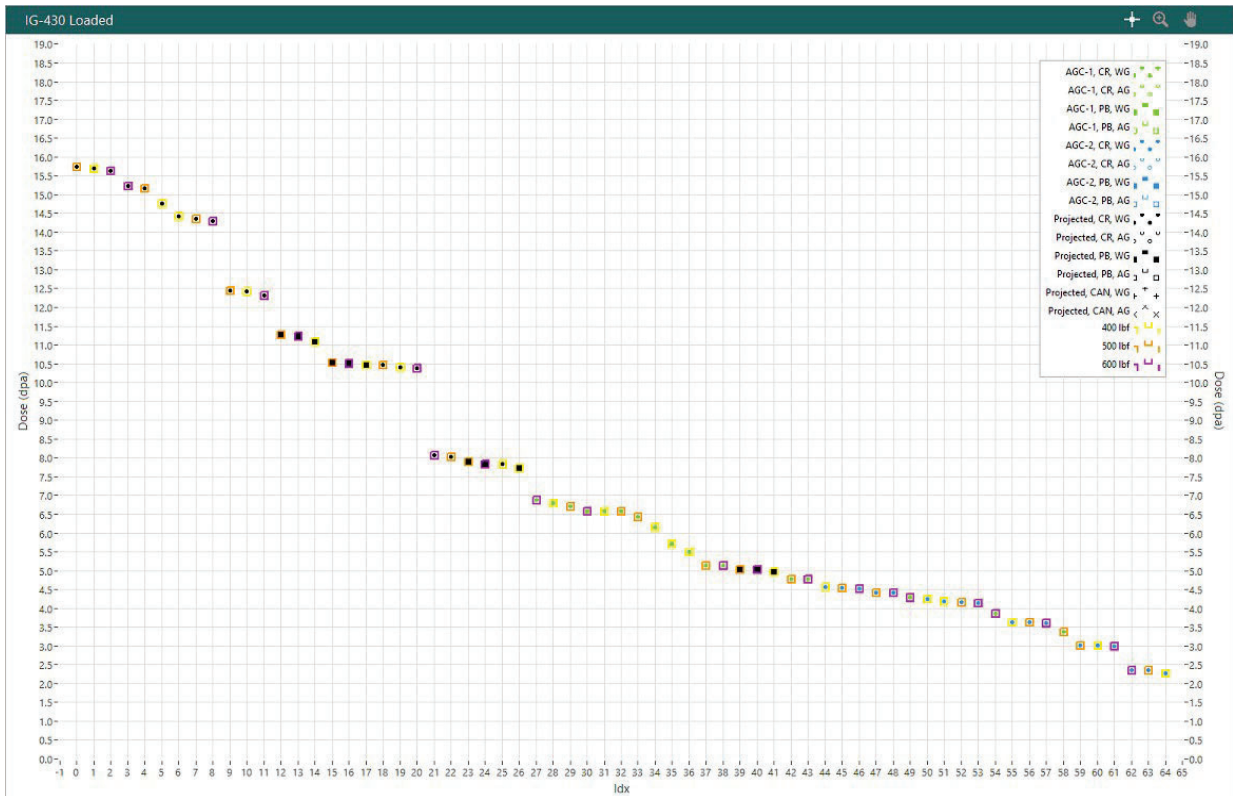


Figure D-3. IG-430 loaded specimens estimated dose profile for HDG-1.

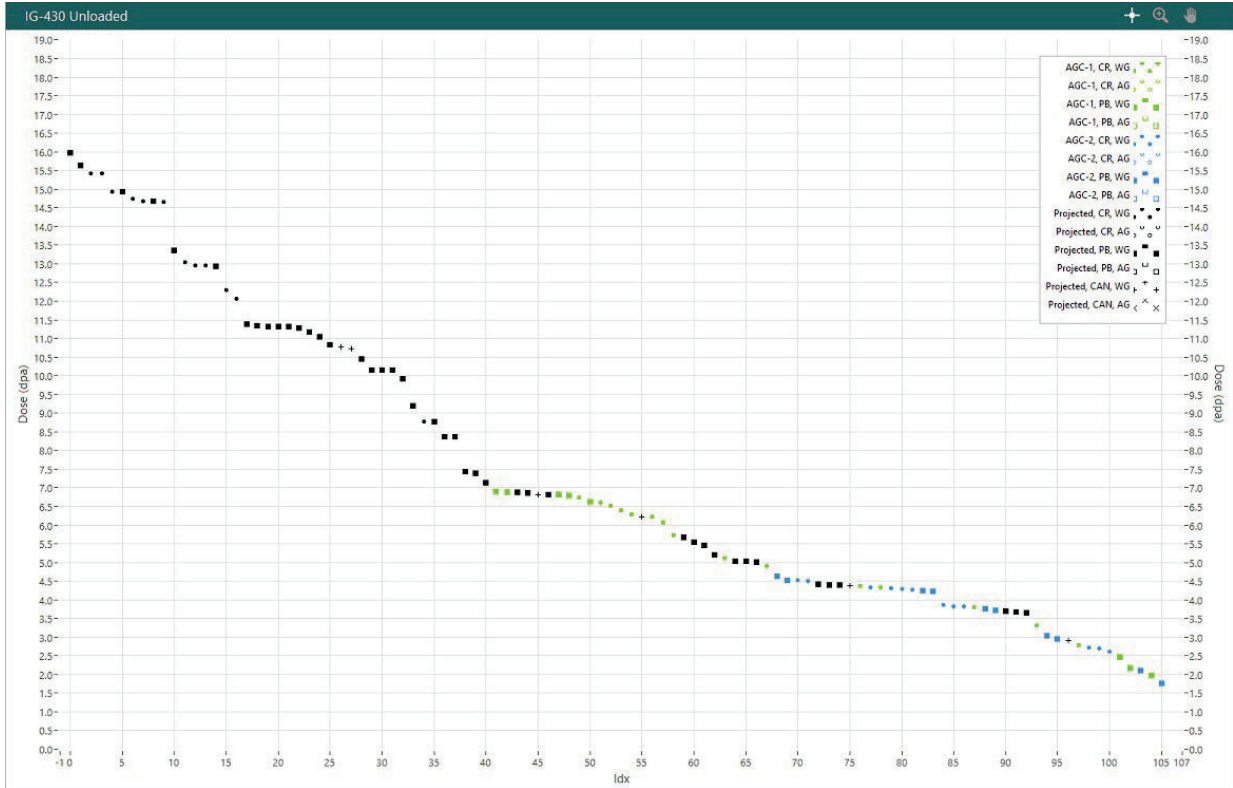


Figure D-4. IG-430 unloaded specimens estimated dose profile for HDG-1.

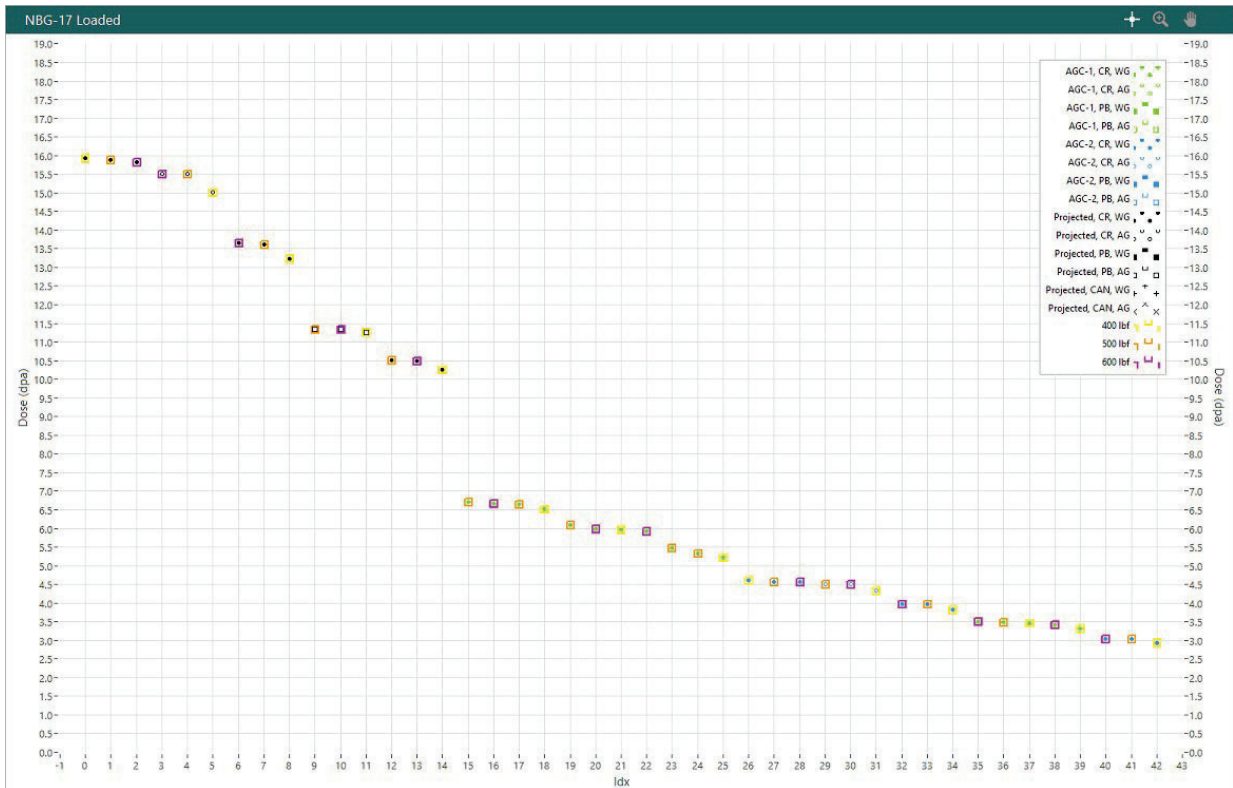


Figure D-5. NBG-17 loaded specimens estimated dose profile for HDG-1.

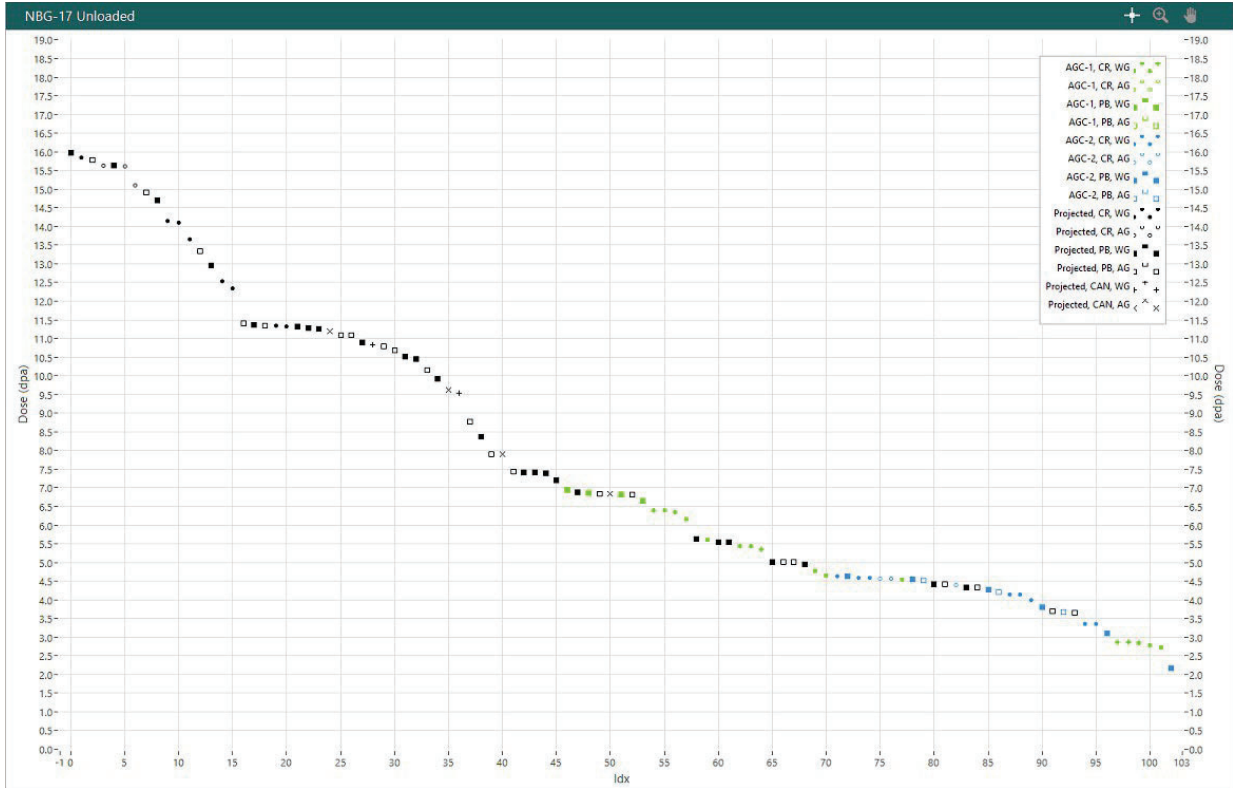


Figure D-6. NBG-17 unloaded specimens estimated dose profile for HDG-1.

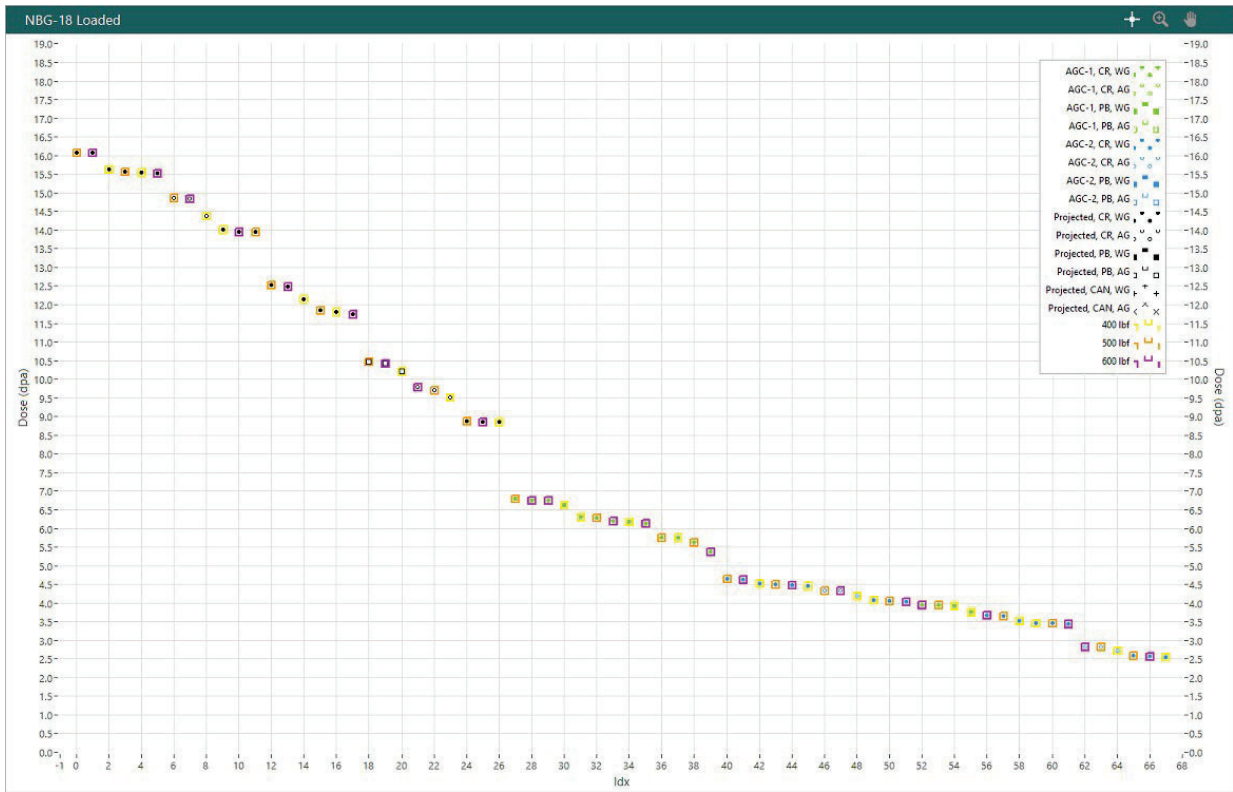


Figure D-7. NBG-18 loaded specimens estimated dose profile for HDG-1.

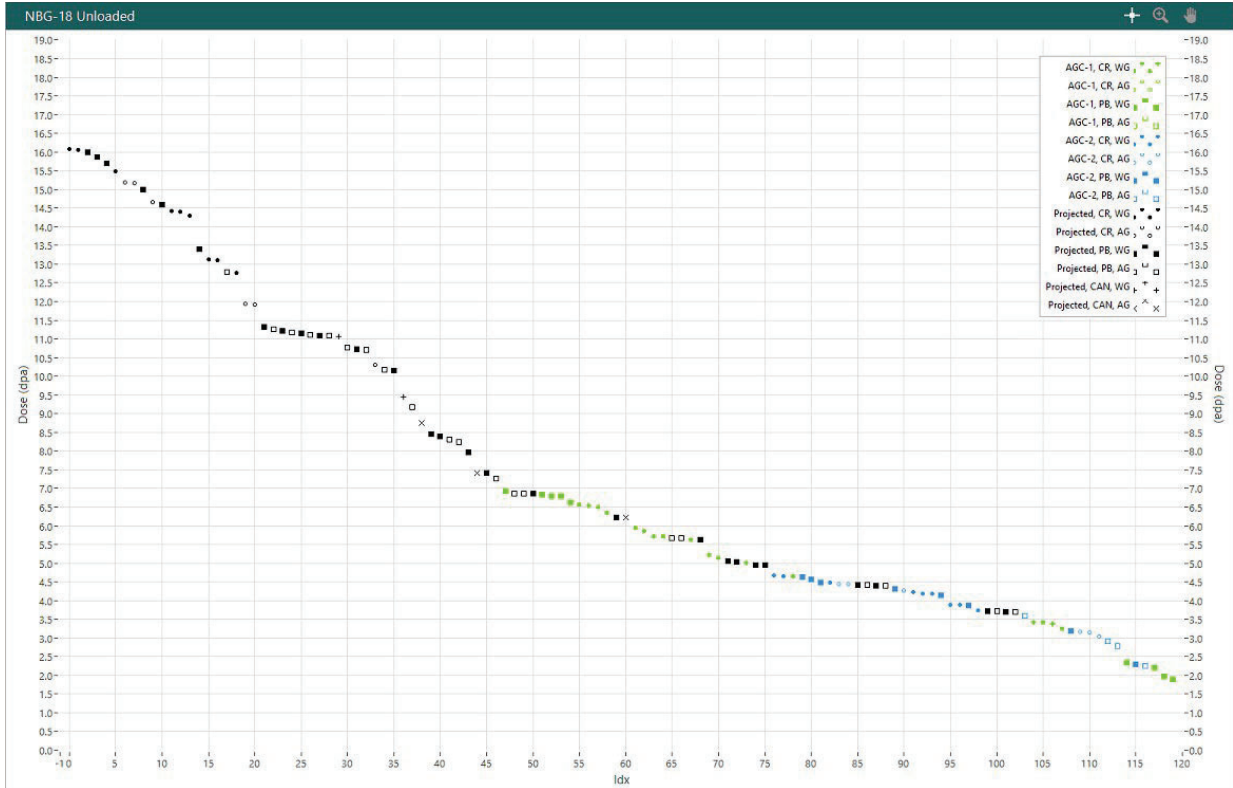


Figure D-8. NBG-18 unloaded specimens estimated dose profile for HDG-1.

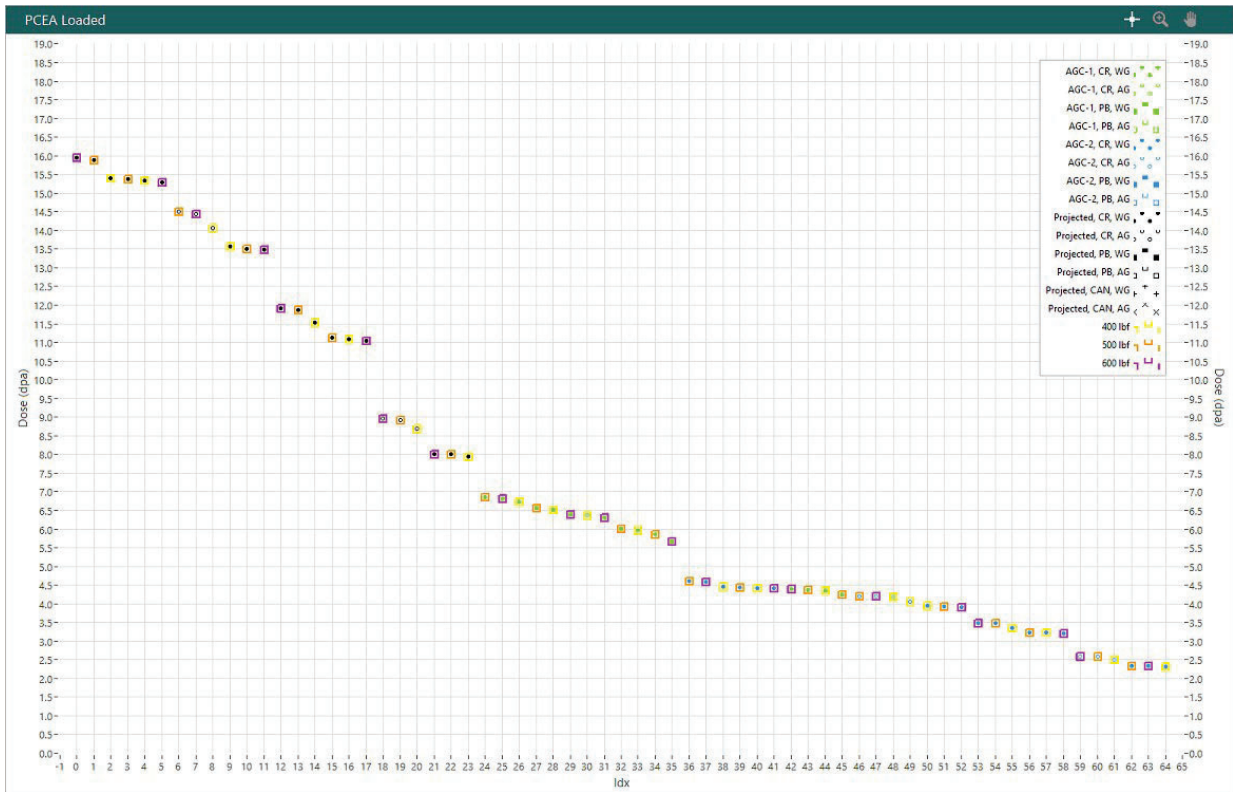


Figure D-9. PCEA loaded specimens estimated dose profile for HDG-1.

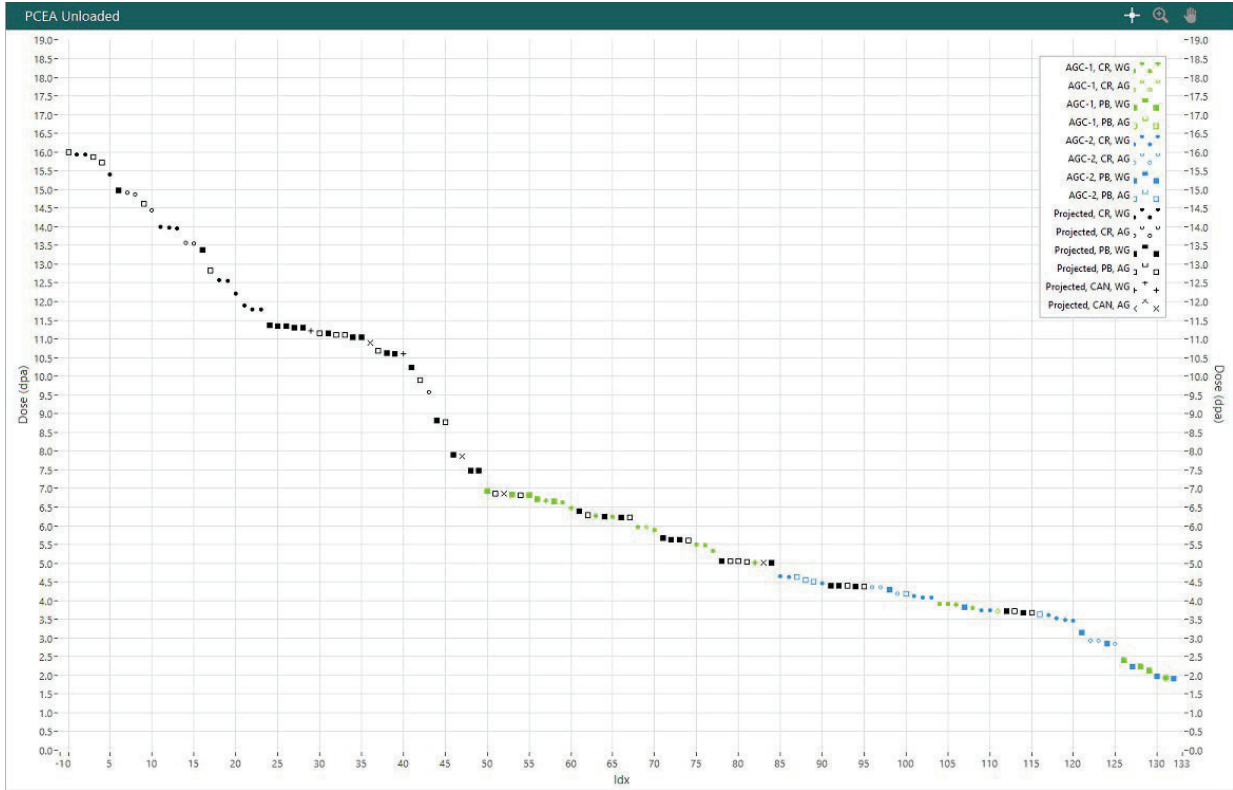


Figure D-10. PCEA unloaded specimens estimated dose profile for HDG-1.