Oxidation Penetration in Nuclear Graphite

INL/RPT-24-80252
Revision 0

Advanced Reactor Technologies

Post-Oxidation Density Evaluation of 7 Grades: 2114, ET-10, ETU-10, IG-110, IG-430, NBG-18, and PCEA

AUGUST 2024

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

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SUMMARY

Study results are presented for seven grades of graphite where 21 cylindrical samples were oxidized to a nominal level of mass loss. Low-mass-loss samples exhibited ~3% oxidative mass loss, intermediate ~8%, and high ~11%. Flat sample surfaces were covered during oxidation to minimize oxidation penetration at the top and bottom of each sample. Oxidized samples had their diameters reduced stepwise in 1-mm or 2-mm increments. Residual samples were weighed, geometric dimensions were recorded, and Archimedes measurements were taken at each step. Preliminary comparative graphical analysis is presented to illustrate the resultant density gradients observed. Raw tabular data are also provided.

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ACKNOWLEDGEMENTS

The author would like to recognize Arvin Cunningham and Mary Kaye Ames of Idaho National Laboratory (INL) for collecting the multitude of data required for this study, Rick Hatch of INL for his meticulous effort iteratively machining these samples, and Austin Matthews and Will Windes of INL for their many recommendations enabling the successful analysis of these initial results.

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ACRONYMS

ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
INL	Idaho National Laboratory

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Oxidation Penetration in Nuclear Graphite

1. INTRODUCTION

Graphite is used for neutron moderation in nuclear reactors and as a structural material in new reactor designs. As long as nuclear graphite is adequately protected from oxidizing gases (moisture, carbon dioxide, and oxygen [air]) the material performs well at high temperatures (600–1200°C). However chronic oxidation is inevitable with exposure to trace contaminants in the coolant, and acute oxidation may occur under postulated accident conditions. In addition to concentration and species of oxidant, temperature and grade of material influence not only the rate of oxidation, but also the gradient of density (location of degradation) established as the reaction progresses. In this context, the 2023 edition of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section II Division 5 Subsection HHA, acknowledges the need for evaluation of the effects of oxidation on graphite performance. ASME BPVC calls for uniformly oxidized graphite specimens for subsequent property determination.[1] This investigation of oxidation penetration depth explores the practical implications of defining and achieving uniform oxidation. Because temperature has the largest observed effect on oxidation penetration depth, the low temperature of 500°C was employed. Air was used as the oxidant both for convenience and to allow for measurable oxidation to occur over a reasonable experiment duration (weeks, not years).

2. MATERIALS AND PREPARATION

Seven grades of graphite were selected for this study to examine the evolution of density gradient after three levels of oxidation (21 graphite samples). The grades tested were 2114, ET-10, ETU-10, IG-110, IG-430, NBG-18, and PCEA. These grades were selected to illustrate the performance of a wide range of nuclear grades of graphite, including multiple manufacturers, production processes, variations in grain size, and in coke source (see Table 1). Each virgin sample was machined from its source billet as a right circular cylinder, 50 mm diameter by 25 mm tall. Samples were cleaned and weighed with geometric measurements (height and diameter) recorded before, at intervals throughout and following oxidation.

Due to slow oxidation (requiring up to six weeks) and the laborious lathing process, this study is limited to three samples for each graphite grade, allowing only minimal statistical analysis with undisputed potential for bias. However, independently determined density data are also available for these same graphite grades via either the Baseline Characterization effort or another oxidation (rate determination) study. Statistical analyses for the geometric density data are offered in Table 2 for perspective on observed variations in the measurement error and specimen-to-specimen determined density for virgin samples for each grade.

This study examined three levels of oxidative mass loss: low, intermediate, and high. Because oxidation was conducted concurrently in batches, the three targeted levels of oxidative mass loss resulted in a range of observed oxidation performance: low (1.95–3.92%), intermediate (7.01–9.87%), and high (9.60–12.74%). For each grade tested, Sample 1 was designated to sustain a low-mass loss; Sample 2, and intermediate-mass loss, and Sample 3, (relatively) high-mass loss. Table 2 gives sample by sample oxidation details alongside the virgin sample density data. Nominally the levels of mass loss are ~3%, ~8%, and ~11%. These three data sets serve to illustrate general trends in behavior, but extra care must be taken to account for relative extent of degradation when comparing grade-to-grade performance: some overlap is evident between the intermediate and high levels of oxidative mass loss.

For oxidation, samples were stacked in a box furnace with flat sides (top and bottom) in contact with neighboring samples or with a solid quartz disk to minimize oxidation at the flat ends. Oxidation was conducted in 10 liter-per-minute flowing air, dispersed through a porous quartz stand supporting a stack of up to six samples as indicated in Figure 1. A low (500°C) isothermal oxidation temperature was employed to promote uniform penetration at sample diameter based on the theory of bulk oxidation regimes.[2] Post-oxidation samples were faced (flat surfaces prepared to control for any incidental edge effects and engraved with an identifier at center top for sample traceability) and a full penetration axial center hole (6.34 mm diameter) was drilled to facilitate the precision lathing process. Successive lathing cuts from the diameter of each sample were made in 1 mm and 2 mm steps. In each case, the test was concluded after 26 or 27 cuts because the residual sample could no longer withstand additional lathing.

Table 1. Variations in nuclear graphite grades tested.

Grade	Manufacturer	Process	Coke	Grain Size	Impurity Content[a]
2114	Mercen	Isostatic Press	Pitch	13 μm nominal[b] 15 μm average[c]	Not Available
ET-10	Ibiden	Isostatic Press	Pitch	15 μm[d]	Not Available
ETU-10	Ibiden	Isostatic Press	Pitch	15 μm[b]	Not Available
IG-110	Toyo Tanso	Isostatic Press	Petroleum	20 μm nominal[b,e] 40 μm maximum[c,e]	20 ppm nominal
IG-430	Toyo Tanso	Isostatic Press	Pitch	(same as IG-110) 10 μm[f,g]	Not Available
NBG-18	SGL Carbon	Vibrational Mold	Pitch	360 μm nominal[e] 1600 μm maximum[c,e]	70 ppm nominal
PCEA	GrafTech International	Extrusion	Pitch	120 μm nominal[e] 800 μm maximum[c,e]	20 ppm nominal

a. Aggregate of elemental data from one specimen of each grade (ppm by weight determined by Gas Chromatography Mass Spectroscopy or Inductively Coupled Plasma-Optical Emission Spectroscopy).
b. Arregui-Mena et al., 2022.[3]
c. Contescu et al., 2018.[4]
d. Ibiden web page, 2024.[5]
e. Kane et al., 2011.[6]
f. Jones et al, 2018.[7]
g. El-Genk and Tournier, 2012.[8]

Table 2. Overview of Oxidative Mass Loss Behavior and Comparison of As-Machined Densities Determined by Geometric Analysis by Graphite Grade.

Graphite Grade	Sample Identifier	Oxidative Mass Loss (%)	Oxidation Duration (days at 500°C)	Pre-Oxidation Density by Sample (g/cc)	Pre-Oxidation Density for the Grade (g/cc)	Baseline or Other Density by Grade (g/cc)	Number of Samples Supporting Baseline or Other Density
2114	Sample 1	3.58	5.7	1.809	1.8105 ±0.0013	1.8112 ±0.0061	885
	Sample 2	7.69	10.5	1.812			
	Sample 3	12.23	14.5	1.810			
ET-10	Sample 1	1.95	11.0	1.785	1.7855 ±0.0012	1.7584 ±0.0029	11*
	Sample 2	6.65	29.2	1.785			
	Sample 3	10.09	33.7	1.787			
ETU-10	Sample 1	1.97	9.4	1.737	1.7390 ±0.0072	1.7351 ±0.0183	29*
	Sample 2	7.01	22.3	1.733			
	Sample 3	9.97	28.7	1.747			
IG-110	Sample 1	3.92	15.7	1.755	1.7629 ±0.0076	1.7758 ±0.1138	492
	Sample 2	7.68	23.3	1.770			
	Sample 3	12.74	28.4	1.764			
IG-430	Sample 1	3.48	26.3	1.788	1.7880 ±0.0040	1.8152 ±0.0071	86
	Sample 2	9.87	42.3	1.784			
	Sample 3	9.60	43.4	1.792			
NBG-18	Sample 1	3.86	15.7	1.843	1.8451 ±0.0031	1.8430 ±0.0144	1155
	Sample 2	8.02	28.6	1.849			
	Sample 3	11.33	41.2	1.844			
PCEA	Sample 1	3.50	4.5	1.838	1.8413 ±0.0025	1.8348 ±0.0071	310
	Sample 2	8.50	9.5	1.843			
	Sample 3	11.99	13.6	1.842			

* Because neither ET-10 nor ETU-10 has been included in the Baseline Characterization effort to date, other data has been included (from a separate oxidation rate testing study) for these two graphite grades to allow comparison of pre-oxidation geometric densities assessed for a modest number of additional samples beyond the three each prepared for penetration depth analysis.

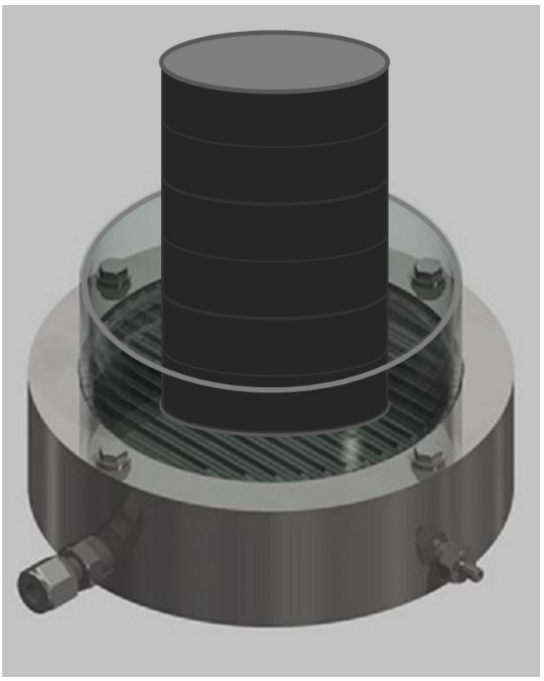

Figure 1. Configuration of samples on diffuser with solid disk during oxidation.

3. METHODS

Two methods of density determination were employed: geometric and Archimedes. Geometric density determination divides the sample weight by the geometric volume (V_G) as assessed from the diameter (d) and height (h) of the cylinder, where $V_G = \pi(d/2)^2h$. Archimedes density determination divides the sample weight by the volume of the sample as assessed by water displacement (after boiling), where the volume (V_A) is the saturated weight minus the suspended weight (based on the density of pure water at ambient temperature and pressure, 1 g/cm^3). These methods are not independent because both require accurate (geometric, dry) weight measurement. Furthermore, because oxidation at 500°C is a slow process (requiring more than 4 weeks to achieve 10% mass loss for most of the grades tested), sample oxidation was begun before the Archimedes instrument was received. Therefore, all density measurements preceding oxidation were solely based on geometric data.

Geometric and weight measurements were taken for each sample between each machining step including facing and drilling of the alignment hole. However, Archimedes measurements were only taken before each diametral cut was made. Geometric and weight measurements are straightforward operations, which were performed using calibrated equipment. Archimedes measurements were taken using a built-to-task instrument and followed the protocol described in ASTM C20 Standard Test Methods for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water, ASTM C20.[9]

4. RESULTS

The tabular data for the geometric and Archimedes measurements for each of the 21 samples at each process step are included Appendix A.

5. ANALYSIS

The PCEA and 2114 graphite grades were the most rapid to oxidize, while IG-430 and NBG-18 were slowest. And ETU-10 and IG-430 seem to show the least penetration approaching the center of the sample: before the residuals began losing integrity, their densities most nearly approached that of the unoxidized samples. In this way, PCEA exhibited the most penetration. These observations reflect a simplified view. Another significant consideration is material performance after oxidation, which requires a step beyond the scope of this work. This study examines the steepness of the density gradient to connect the extent of mass loss (sample density) to the eventual post-oxidation performance testing of graphite samples in a meaningful way.

The most direct approach to density analysis examines the geometric and Archimedes determined densities of the residual samples with each lathing step, Figure 2–Figure 8. For ease of comparison among grades, the density scale (y-axis) spans the full range from 1.50 g/cc where the oxidized material typically loses its physical integrity to the theoretical 2.26 g/cc of perfect crystalline graphite for all 7 graphs. By relying on the minimum number of measurements at each step, the similarities and differences between the two analytical methodologies are most obvious. The blotting procedure used to establish the saturated weight (for determination of V_A) seems particularly imprecise, particularly for (residual) samples with relatively large networked open porosity. Also, the last few cuts (most closely approaching the centering hole) sometimes show nearly as much density loss as the first few cuts. This suggests that the centering hole contributes to loss of sample integrity when the remaining material gets too thin and the calculated density values no longer represent oxidative mass loss with subsequent cuts. In general, the density of the residual at successive steps shows that the internal density of each sample does remain relatively consistent for most grades when oxidized at 500°C.

Local density was calculated from the difference in weights of the residual sample before and after a lathing step divided by the difference in volumes of the residual sample before and after that lathing step. The sample radii midway between the before and after dimensions (calculated from the diameters measured) were used for the location of each local density. Figure 9–Figure 15 illustrate the density gradient for the three levels of oxidative mass loss examined for each grade. Plotted at the same scale as the densities of the residual samples, these graphs provide a somewhat different perspective.

One of the challenges in interpreting these data is the scatter in calculated local density deep within most of the samples included in this study. While channeling of gas flow, local defects in the graphite matrix structure or localized concentrations of catalytic contaminants could conceivably account for unexpected decrease in density within a sample, localized zones of increased density lack any such intuitive mechanistic explanations. These are speculated to be (at least partly) an artifact of the aggregated error for the combination of measurements required for analysis at a local location within any given sample, but the net effect (the extent of scatter) is clearly influenced by the grade-specific microstructure. Observe how closely the local density data for IG-430 Sample 2 (9.87% mass loss in 42.3 days at 500°C) and IG-430 Sample 3 (9.60% mass loss in 43.4 days) track both in Figure 6 and in Figure 13 given the similarities in duration and mass loss.

Looking at any single ~1-mm-wide local density increment requires twice as many discreet measurements because the local density must be determined from the values measured both before and after a cut. The probability that deviations in measured values of mass and volume may aggregate to give a magnified deviation in the calculated density increases substantially (depending on the distribution of values for each type of measurement) as the calculation requires the use of each additional measured value. This aggregation of error is inherent to the non-additive nature of density as a material property and the reliance on additive properties (both weight and volume both before and after a cut) compounds the deviation in the determination of local density.

In each case the (residual or local) density at the sample center (radius = 0) was determined from the weight change upon drilling the hole in combination with the indicated hole diameter (assumed to be uniform over the height of the sample). Note that a few of the geometric densities calculated for the core slightly exceed the calculated density of the unoxidized sample. While necessary to achieve the desired machining precision, the centering hole also contributes to uncertainty in the density determinations. While the weight of the core can be added back for the geometric density analysis for the residuals, that would negate the direct graphical comparison to the Archimedes analysis. Both the geometric and Archimedes densities shown in Figure 2–Figure 8 reflect the residual as weighed (without the core). Numerically, adding the core back for the geometric analysis of any one residual typically adds only ~0.001 g/cc to the calculated density.

Archimedes measurement-derived density data tracks reasonably well with the geometric calculated density data for residual samples. As expected, the samples with the highest oxidative mass loss tend to have the lowest densities across the entire sample and those with the lowest oxidative mass loss tend to have the highest densities across the entire sample (both for densities of the residuals and for local densities). The occurrence of calculated local densities exceeding the bulk density of the virgin sample was common to both the geometric and the Archimedes methodologies for density determination. In most cases, these occurrences of inexplicably high calculated local densities present adjacent to a noticeably lower than anticipated calculated local density. This appears to support the theory of aggregated error because the average tends to revert to the norm.

By assuming that the data from such adjacent lathing steps can be combined to reflect the local performance as accurately as the apparent adjacent extremes (as if a single larger cut had been made), this approach, in conjunction with omission of the last three cuts where the residual samples typically indicate loss of integrity, can be used to smooth the density gradients enabling more direct visual comparison among grades, as shown in Figure 16–Figure 18. Because only the geometric data are available for the virgin samples, the geometric data are shown exclusively in these three figures to illustrate the relative performance of all seven of the grades together for the low-, intermediate-, and high-oxidative mass loss levels, Figure 16–Figure 18, respectively. Here the local density has been normalized by the density of the unoxidized sample to emphasize the relative variations in density profile with grade. The lower the mass loss, the more difficult to distinguish grade-to-grade differences in performance.

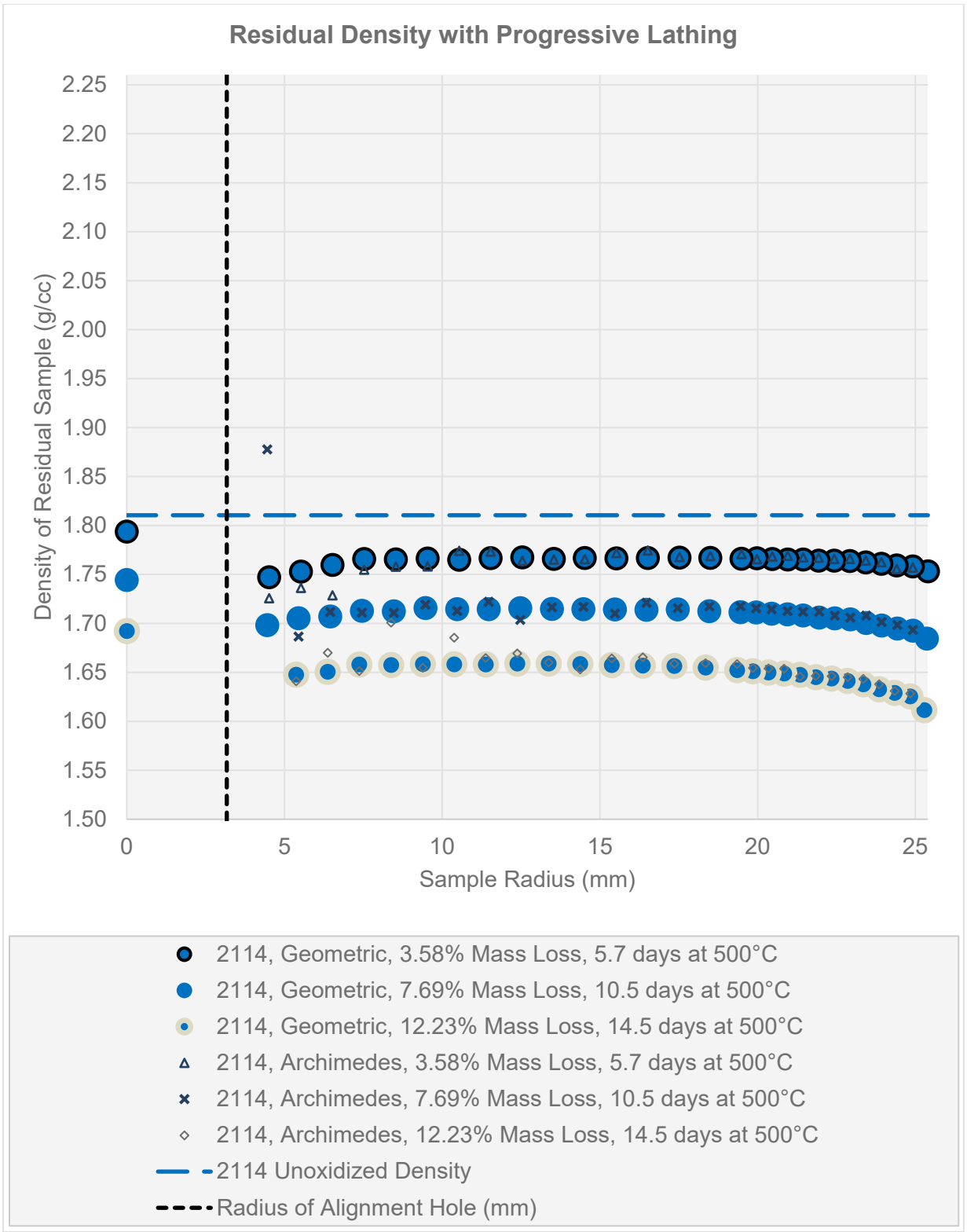

Figure 2. Residual density at each step for 2114 graphite.

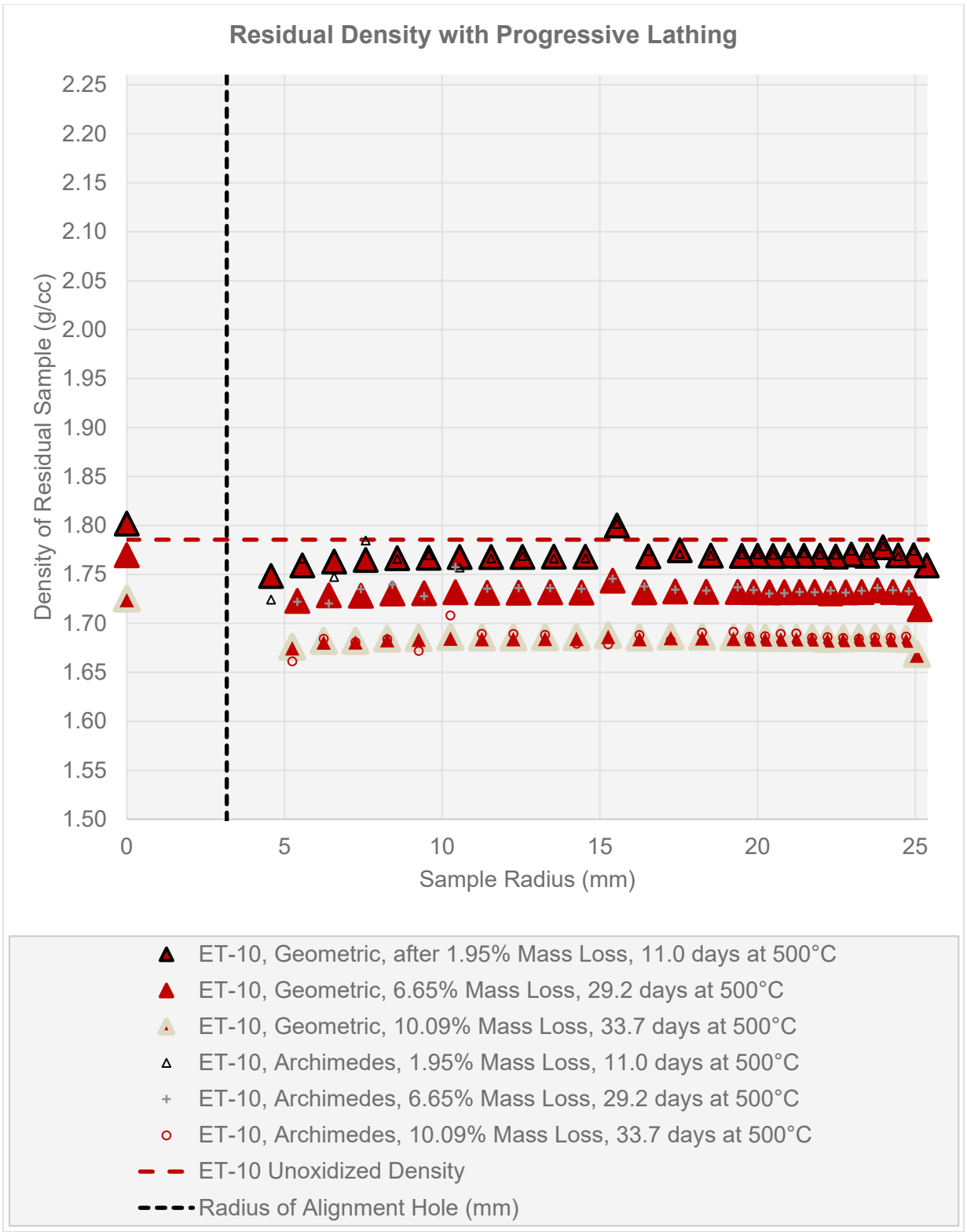

Figure 3. Residual density at each step for ET-10 graphite.

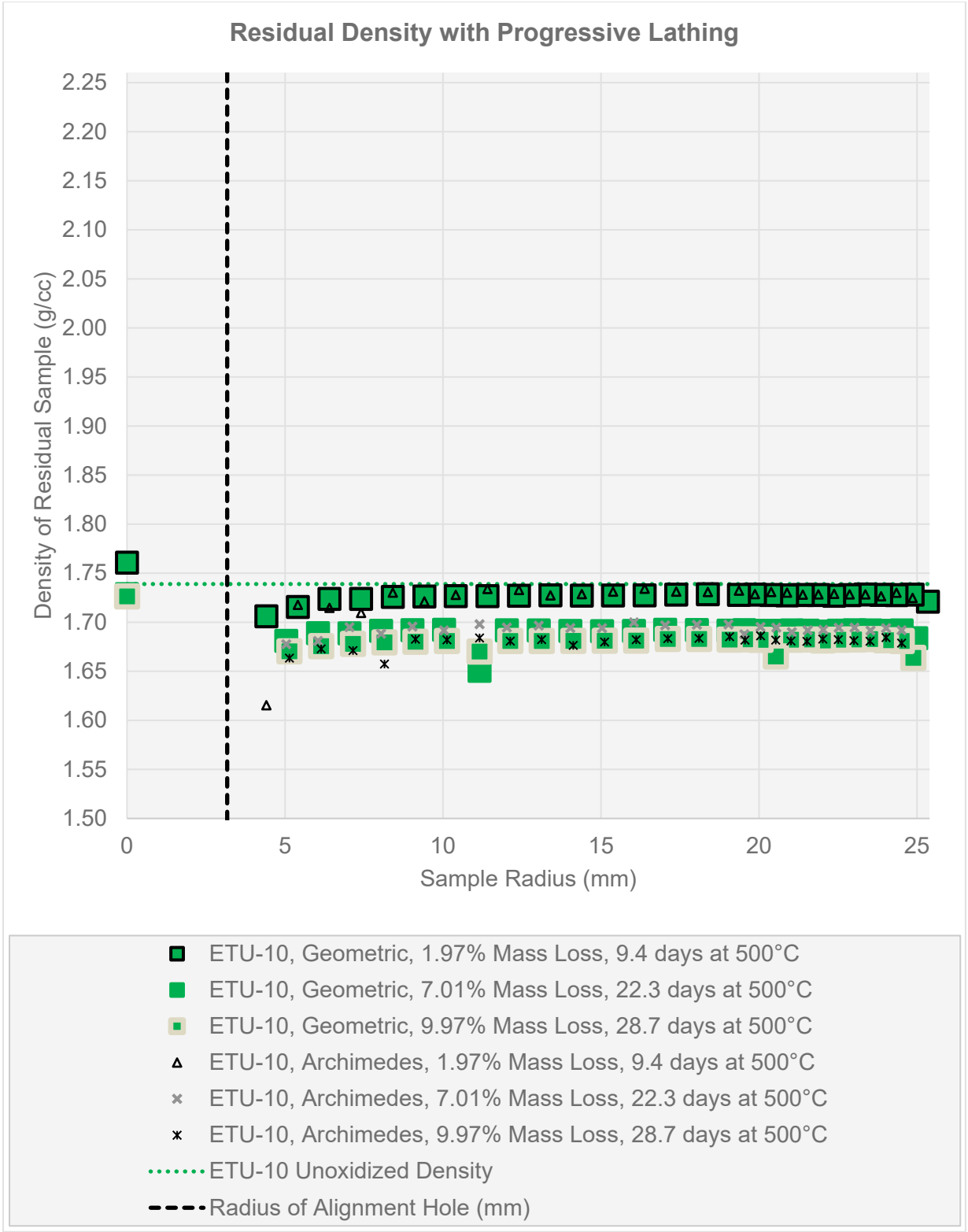

Figure 4. Residual density at each step for ETU-10 graphite.

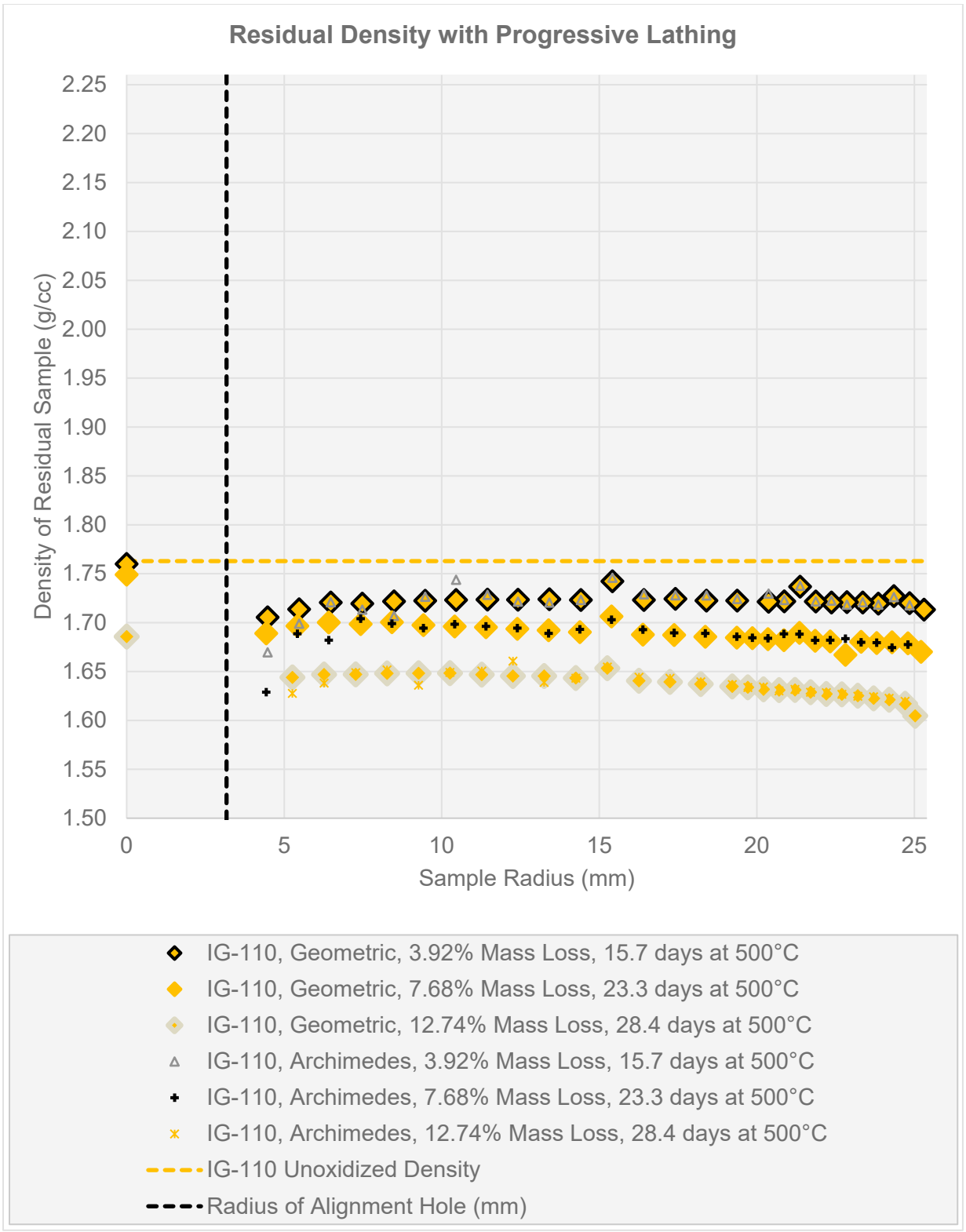

Figure 5. Residual density at each step for IG-110 graphite.

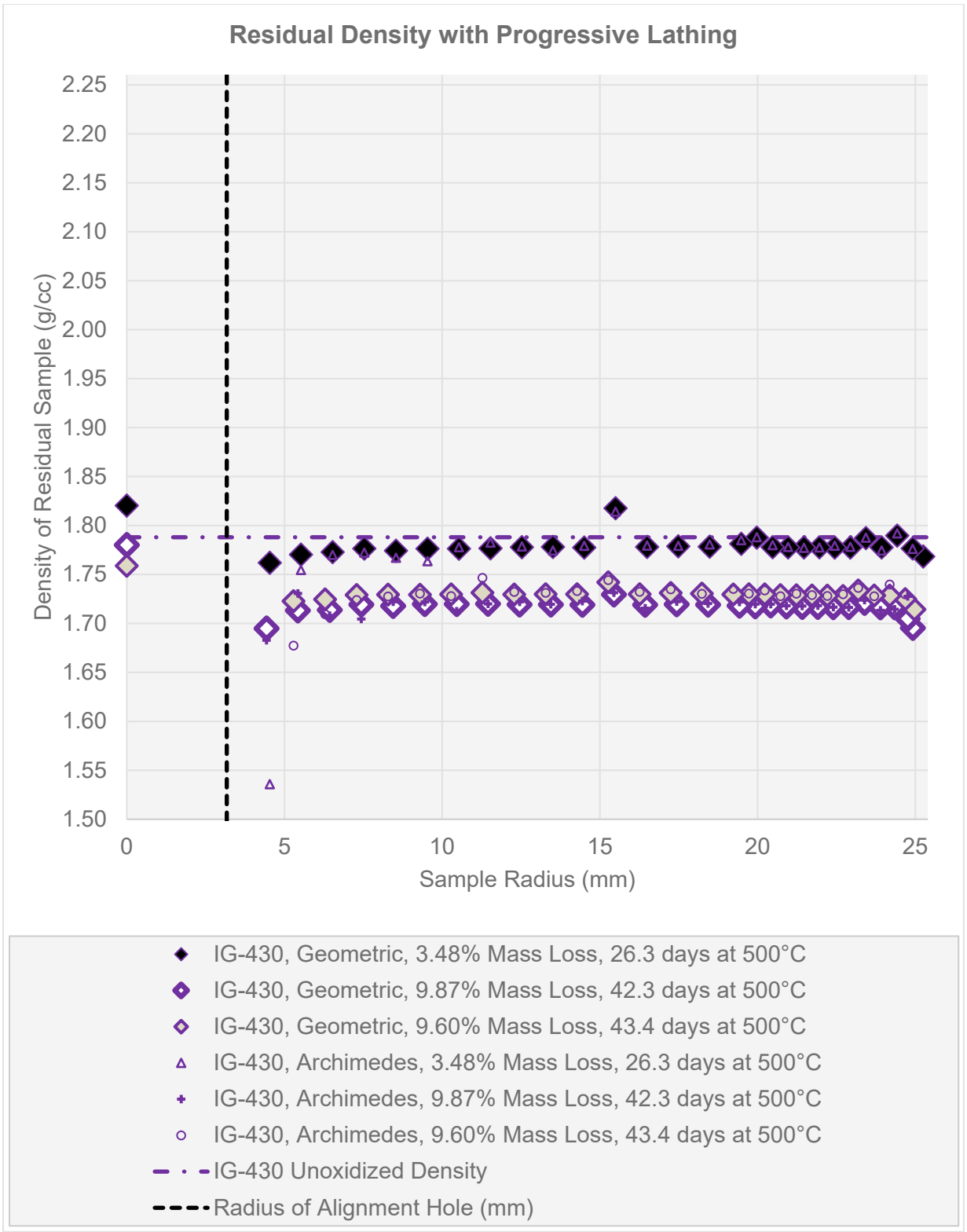

Figure 6. Residual density at each step for IG-430 graphite.

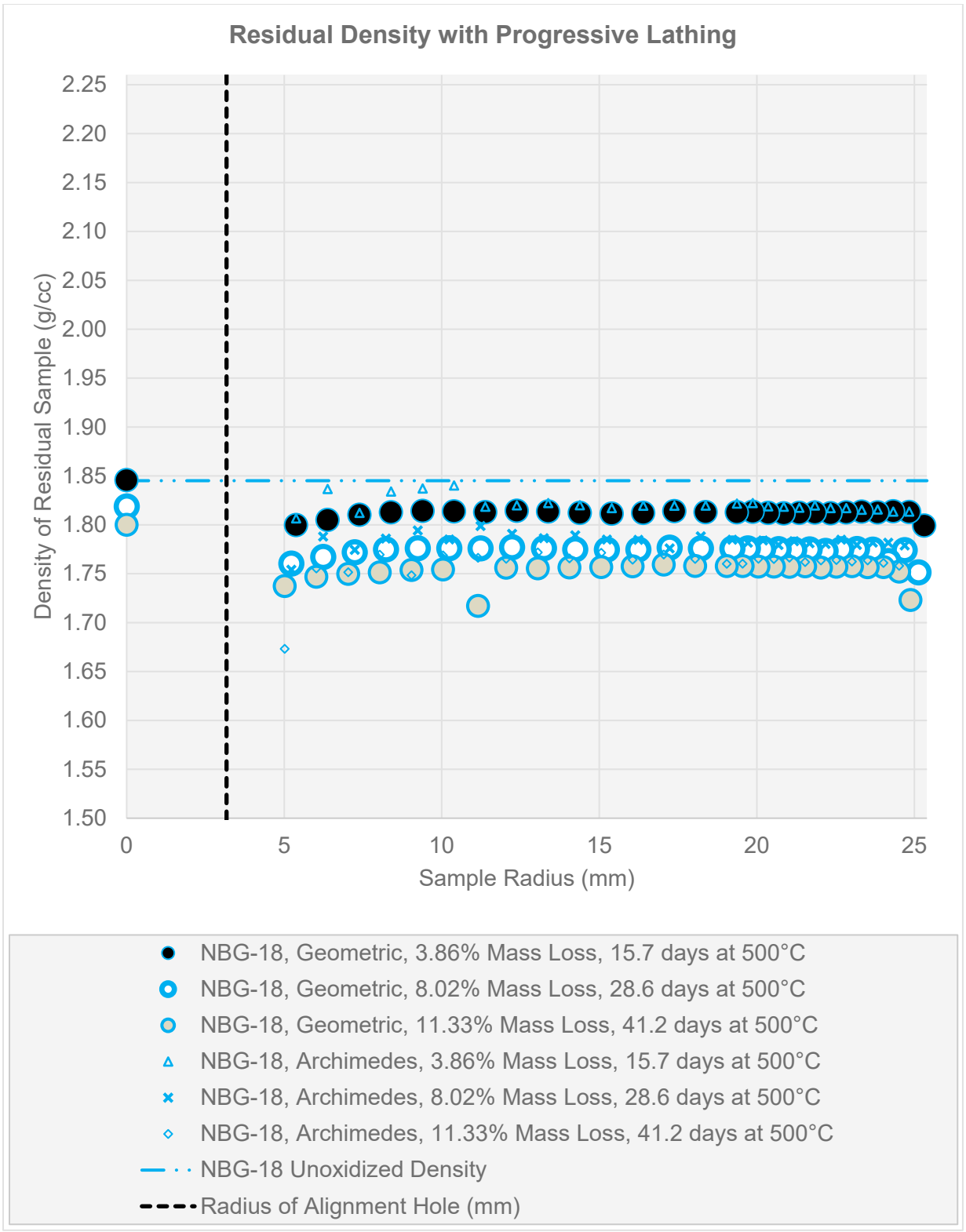

Figure 7. Residual density at each step for NBG-18 graphite.

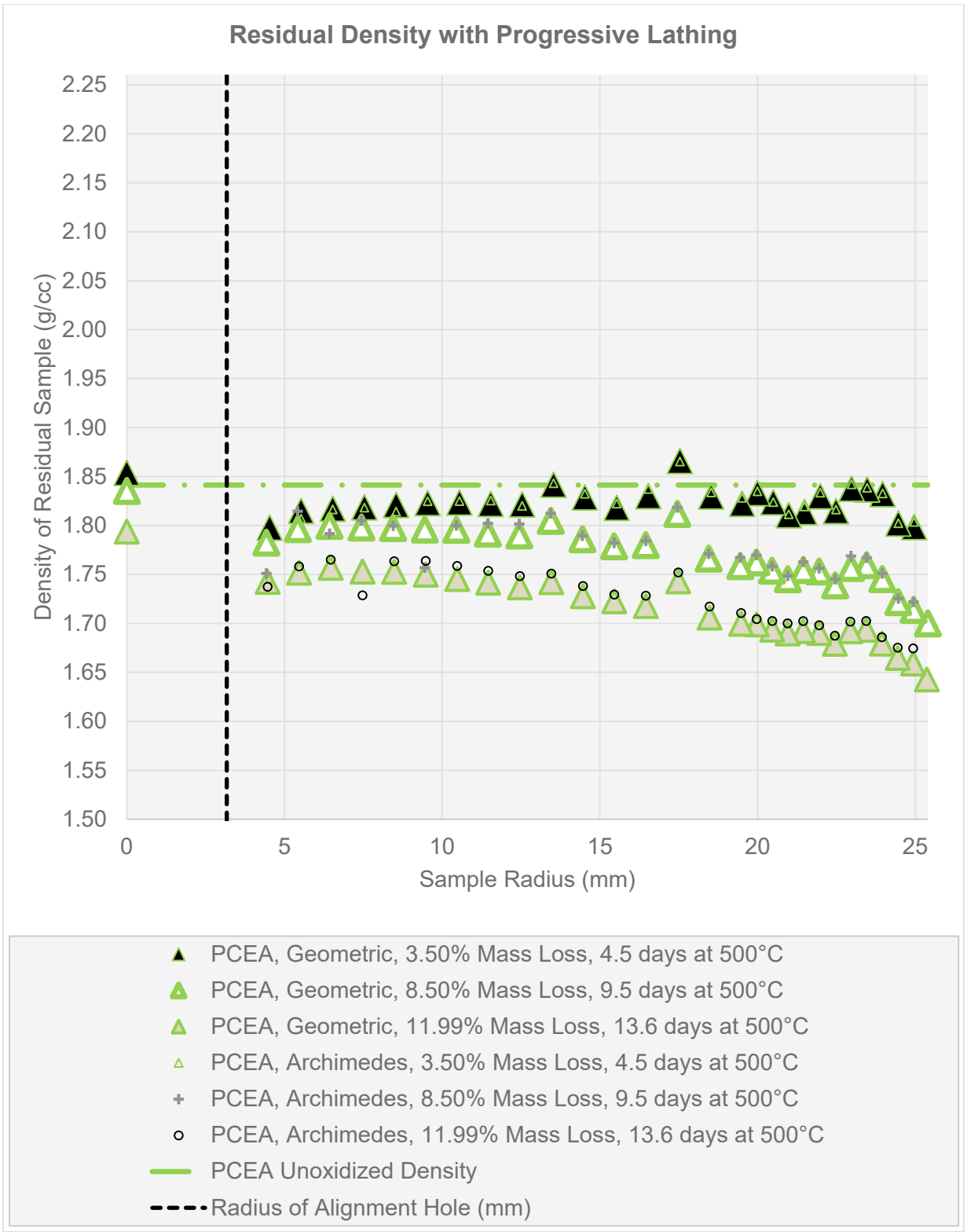

Figure 8. Residual density at each step for PCEA graphite.

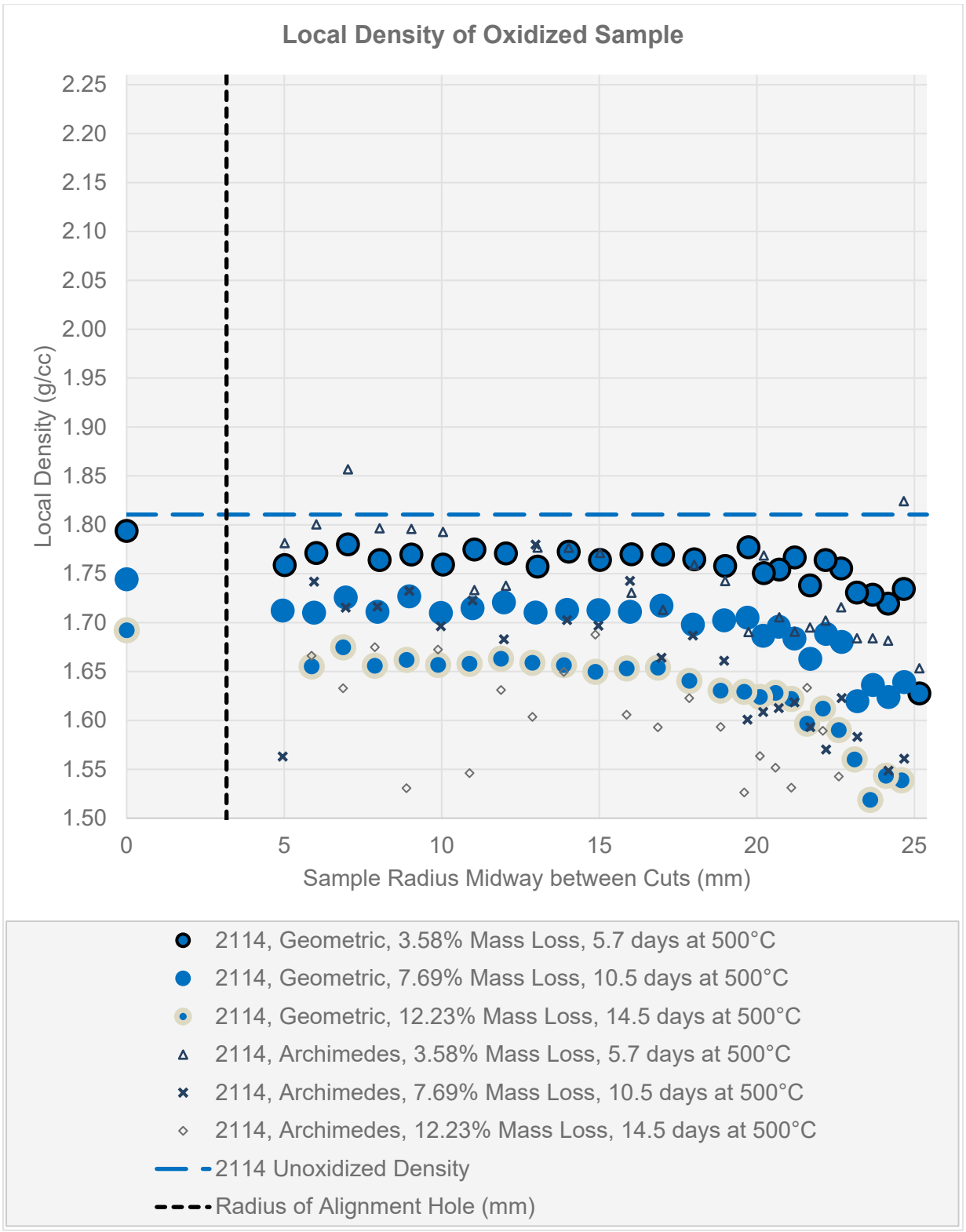

Figure 9. Local density graph for 2114 graphite.

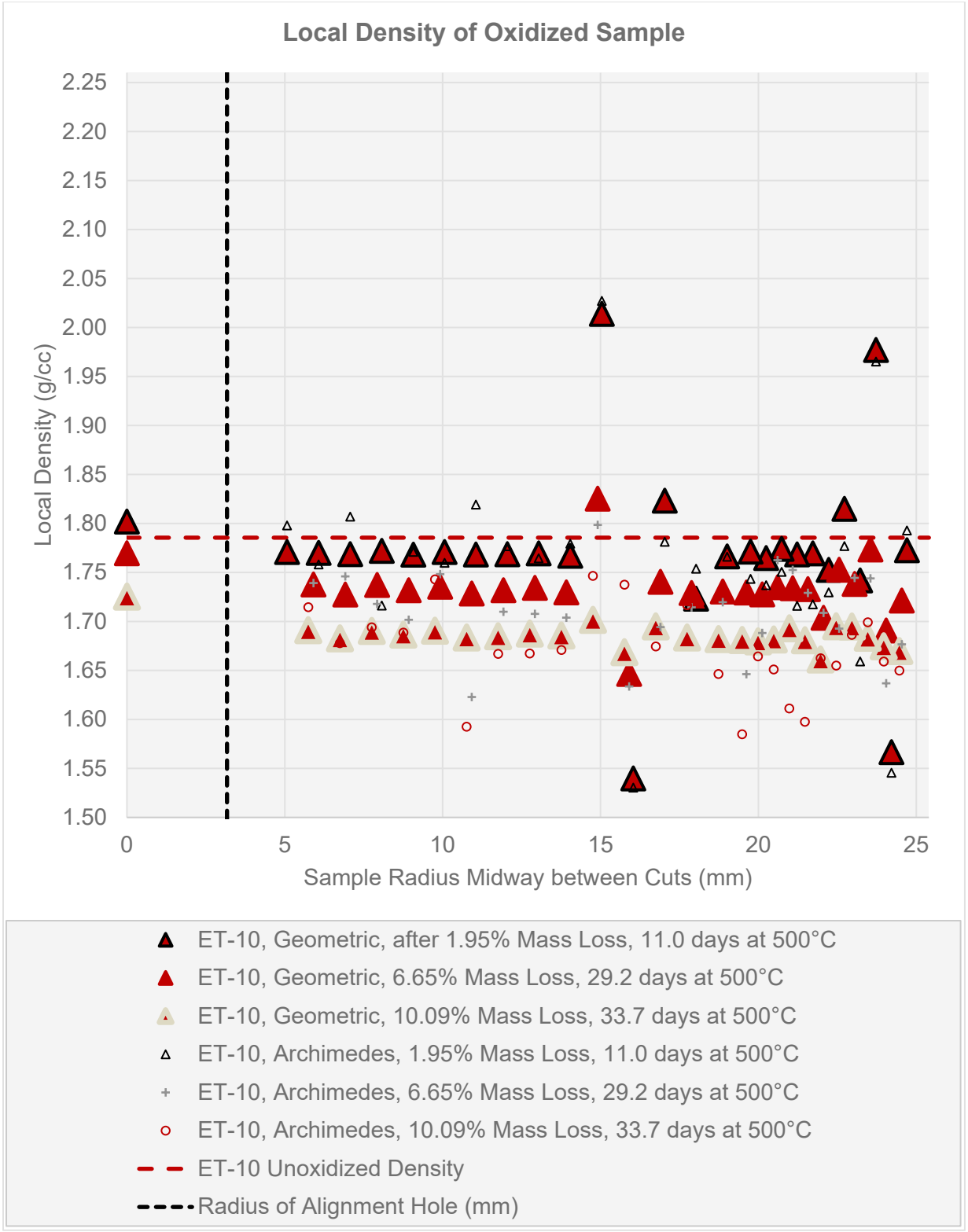

Figure 10. Local density graph for ET-10 graphite.

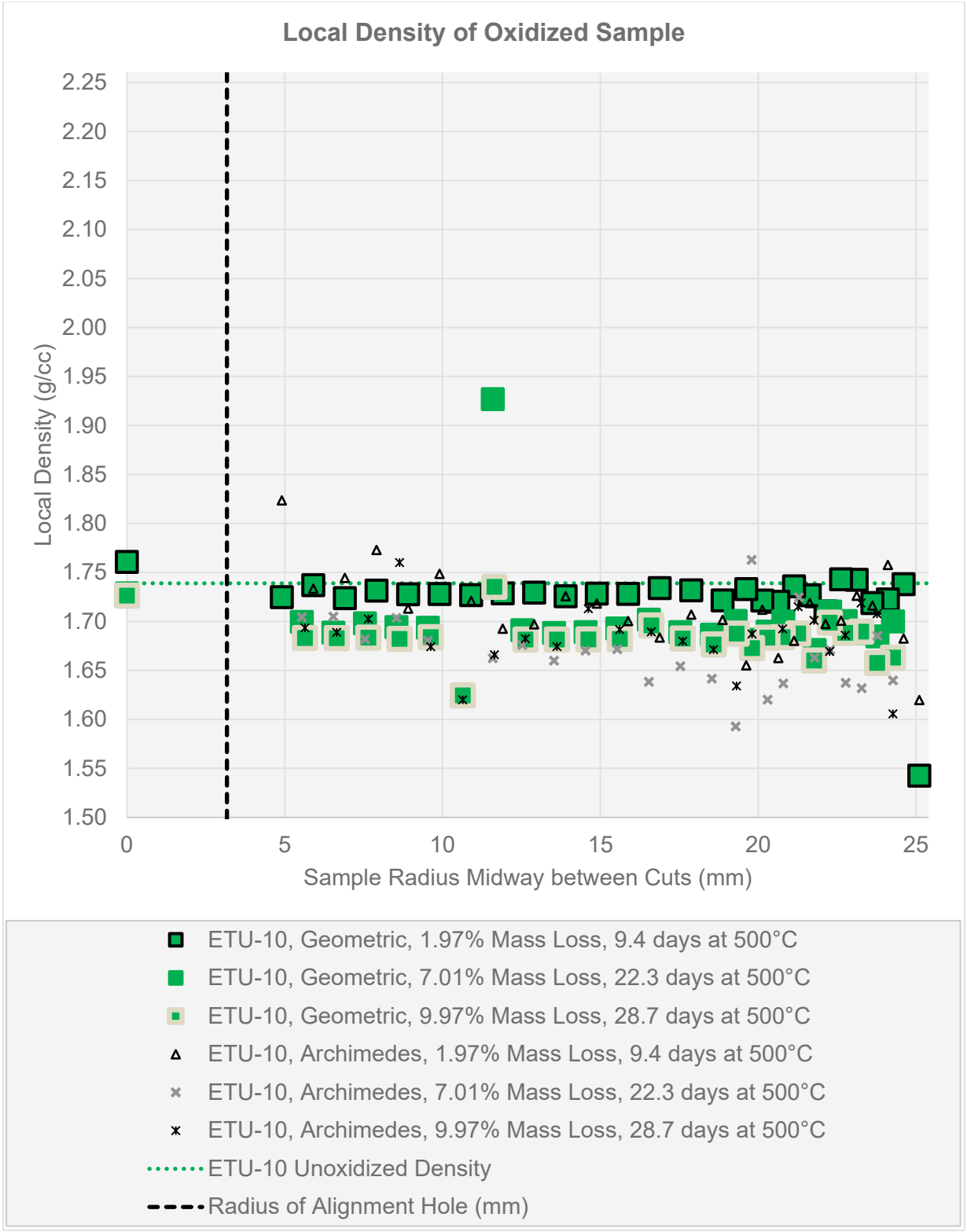

Figure 11. Local density graph for ETU-10 graphite.

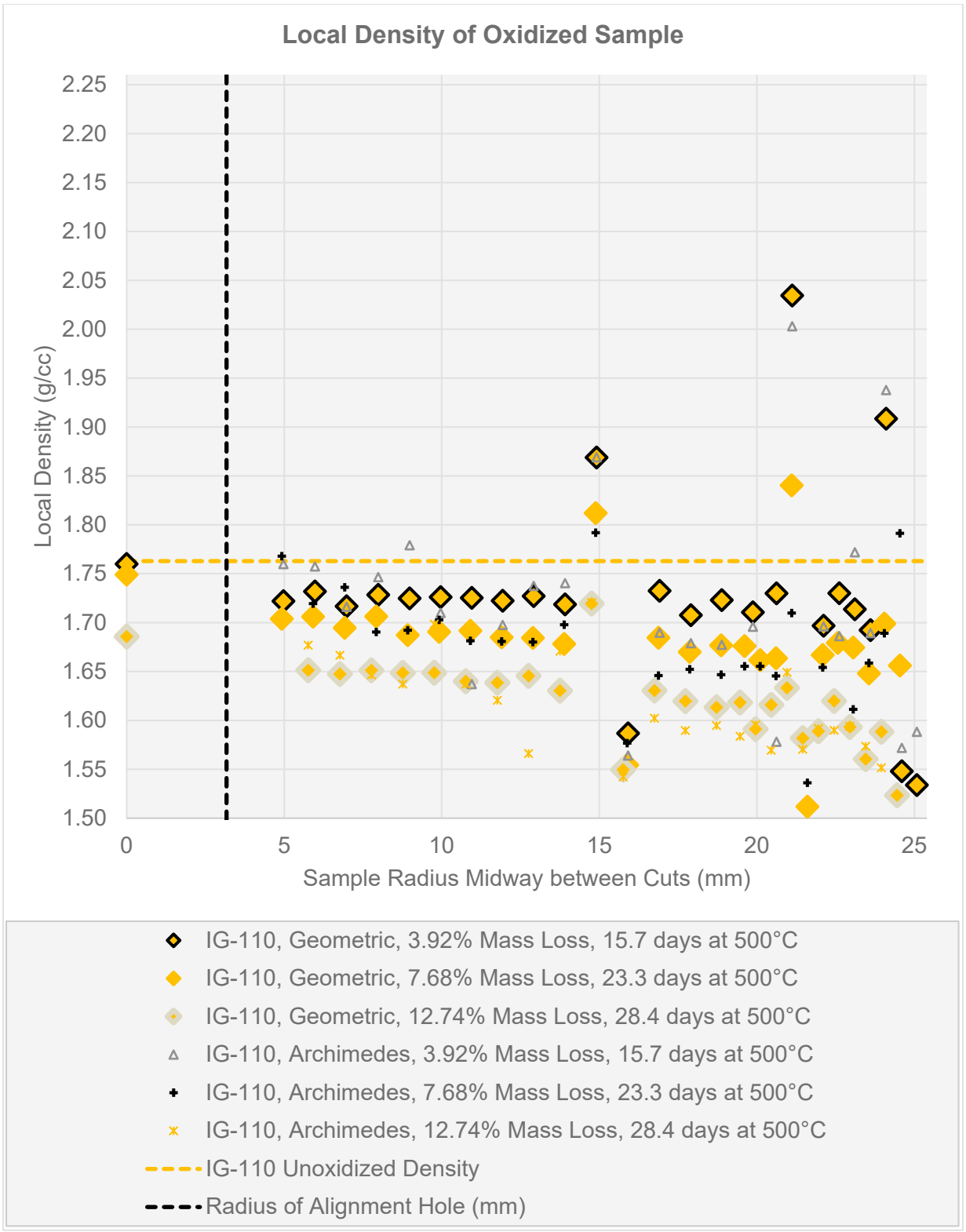

Figure 12. Local density graph for IG-110 graphite.

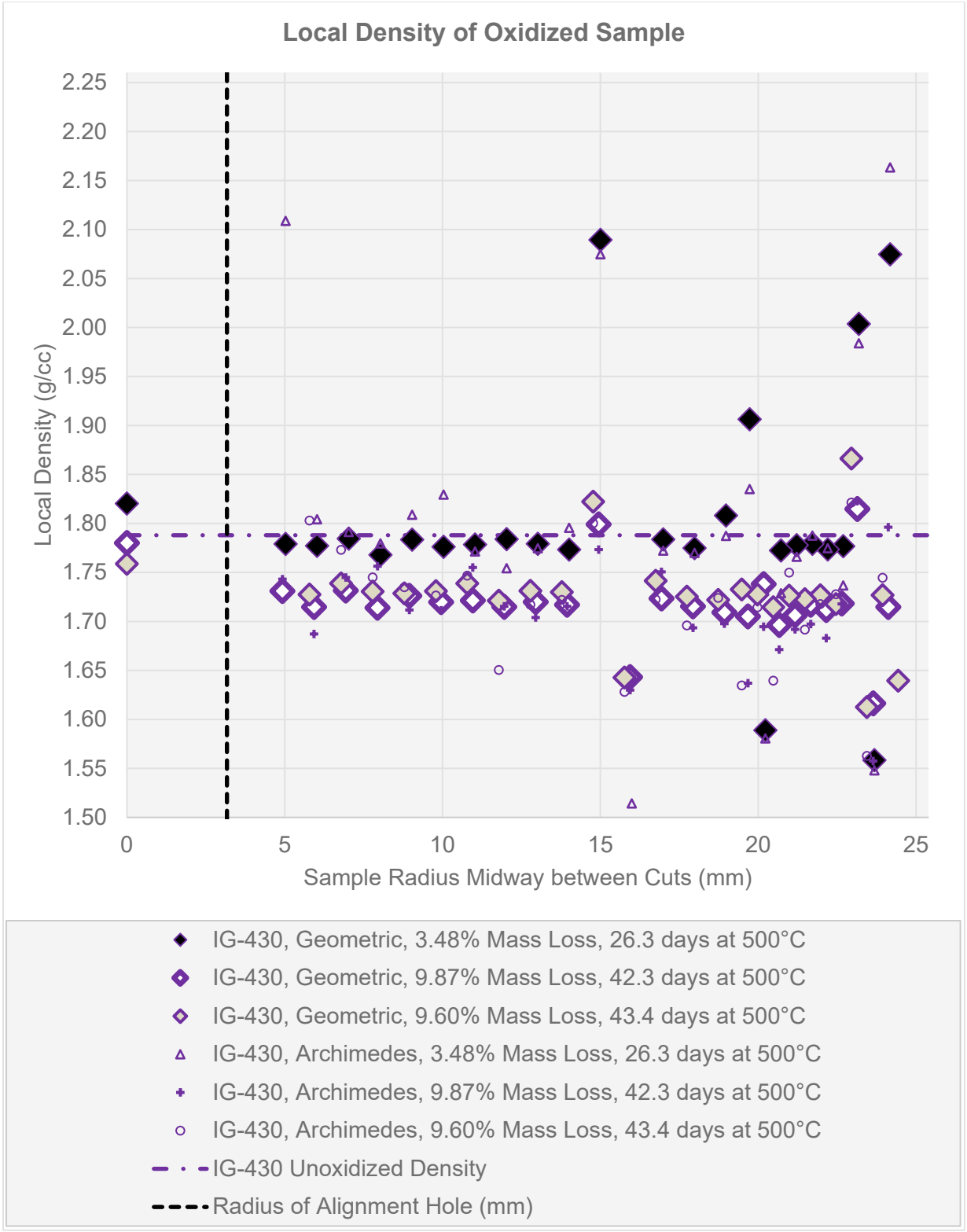

Figure 13. Local density graph for IG-430 graphite.

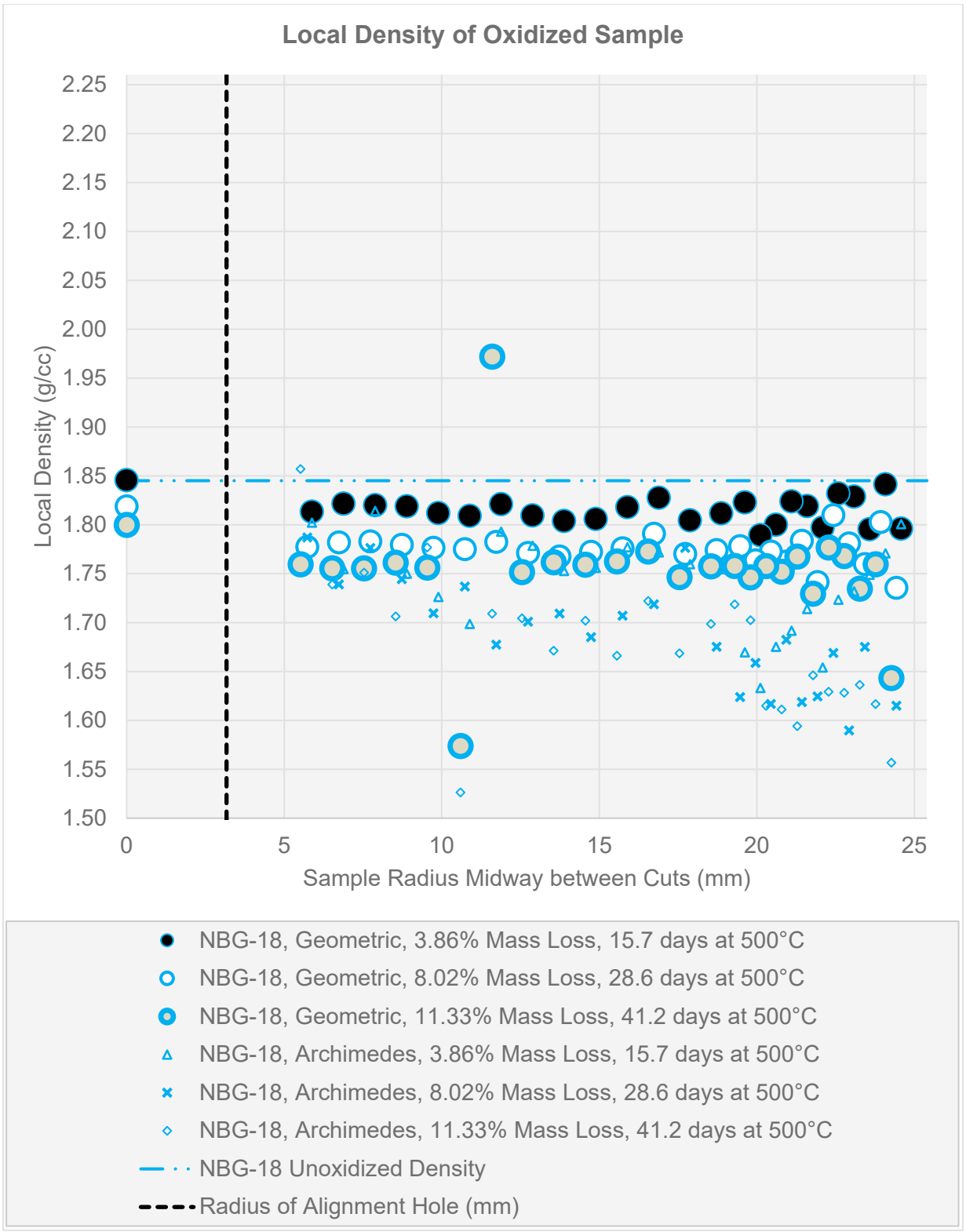

Figure 14. Local density graph for NBG-18 graphite.

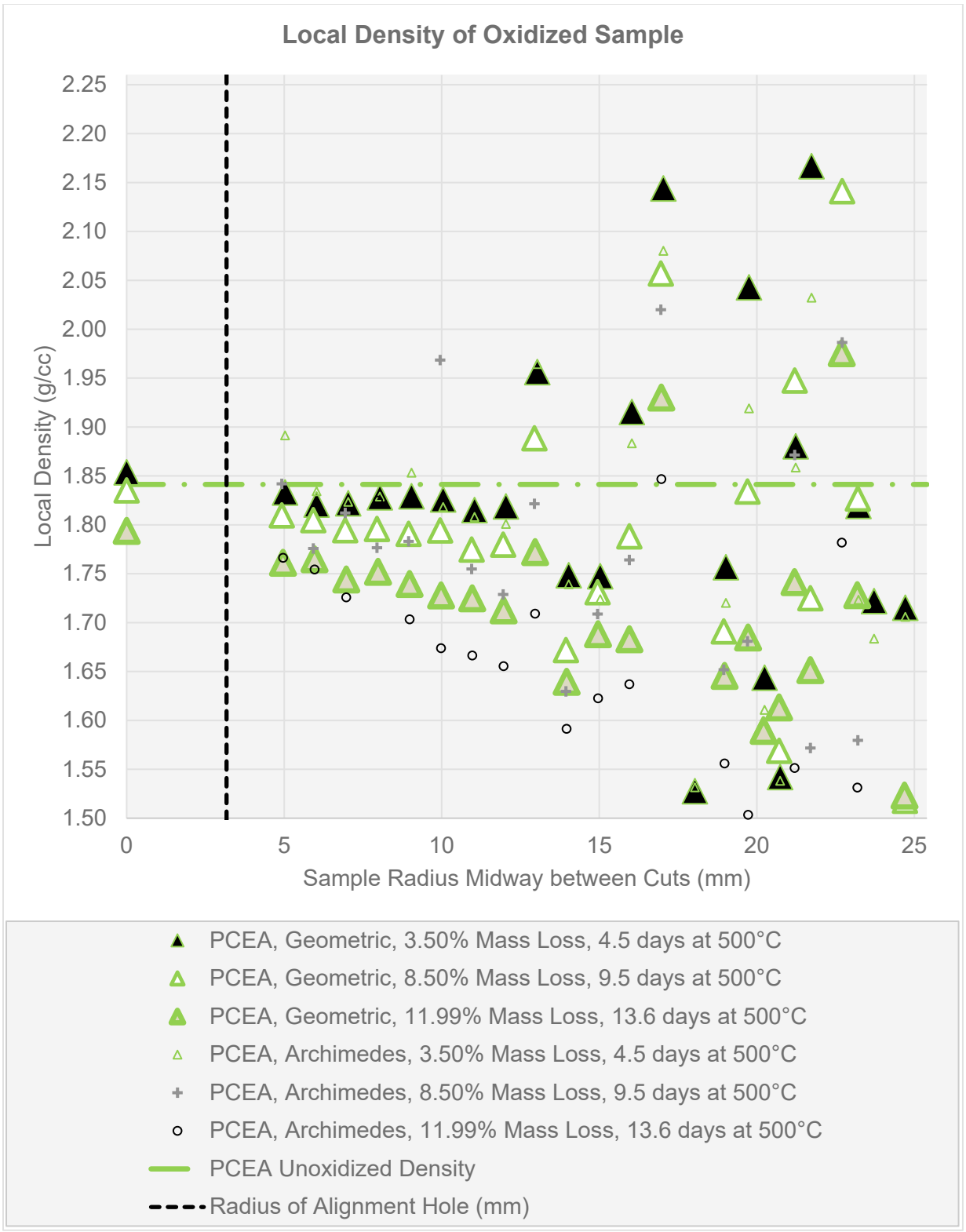

Figure 15. Local density graph for PCEA graphite.

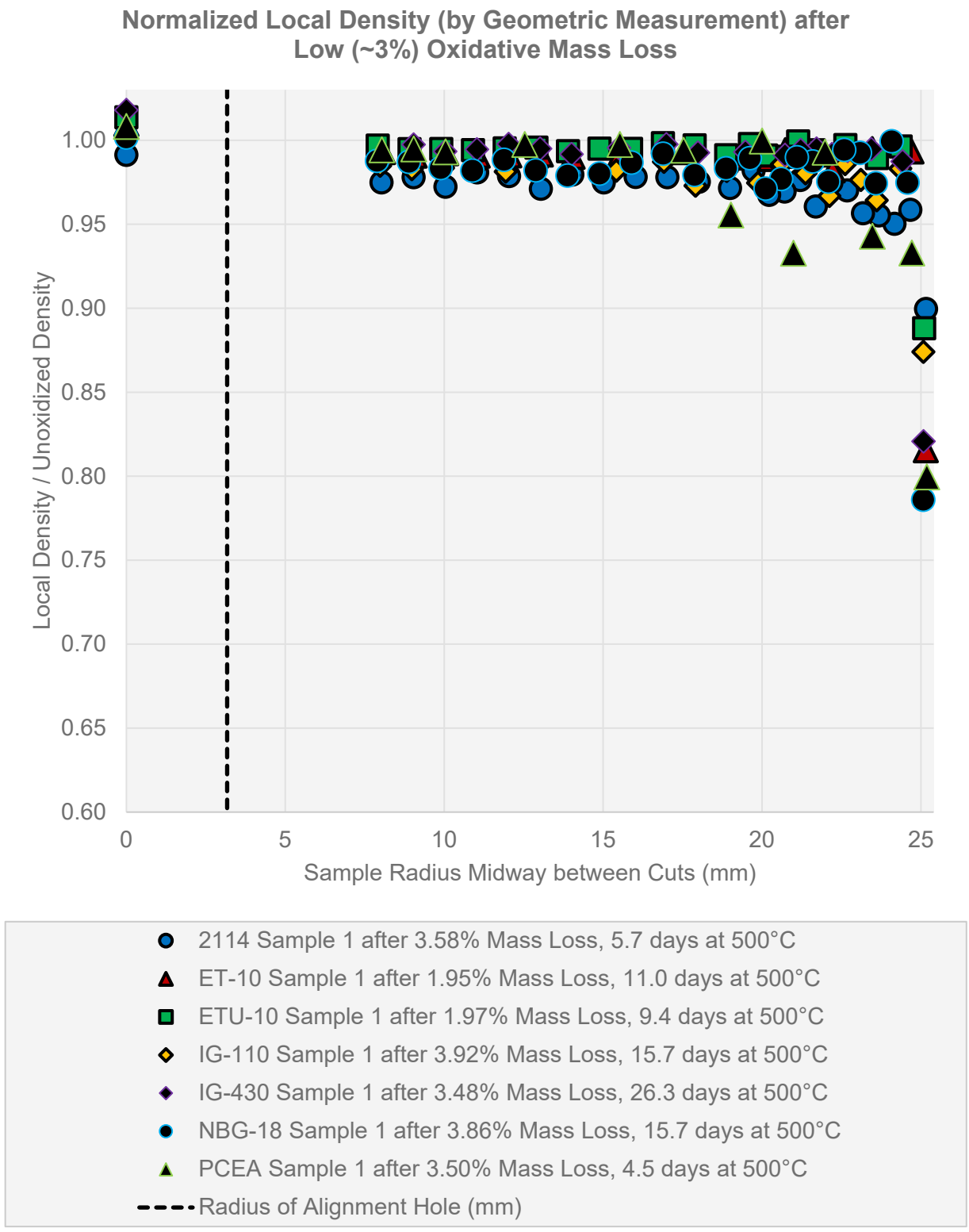

Figure 16. Local density profile (determined by geometric analysis) with sample radius for low-mass-loss samples for seven grades of graphite normalized by the density of the unoxidized sample. Adjacent cuts were combined to avoid apparent local densities greater than that of the unoxidized sample. Does not include data beyond Cut 24.

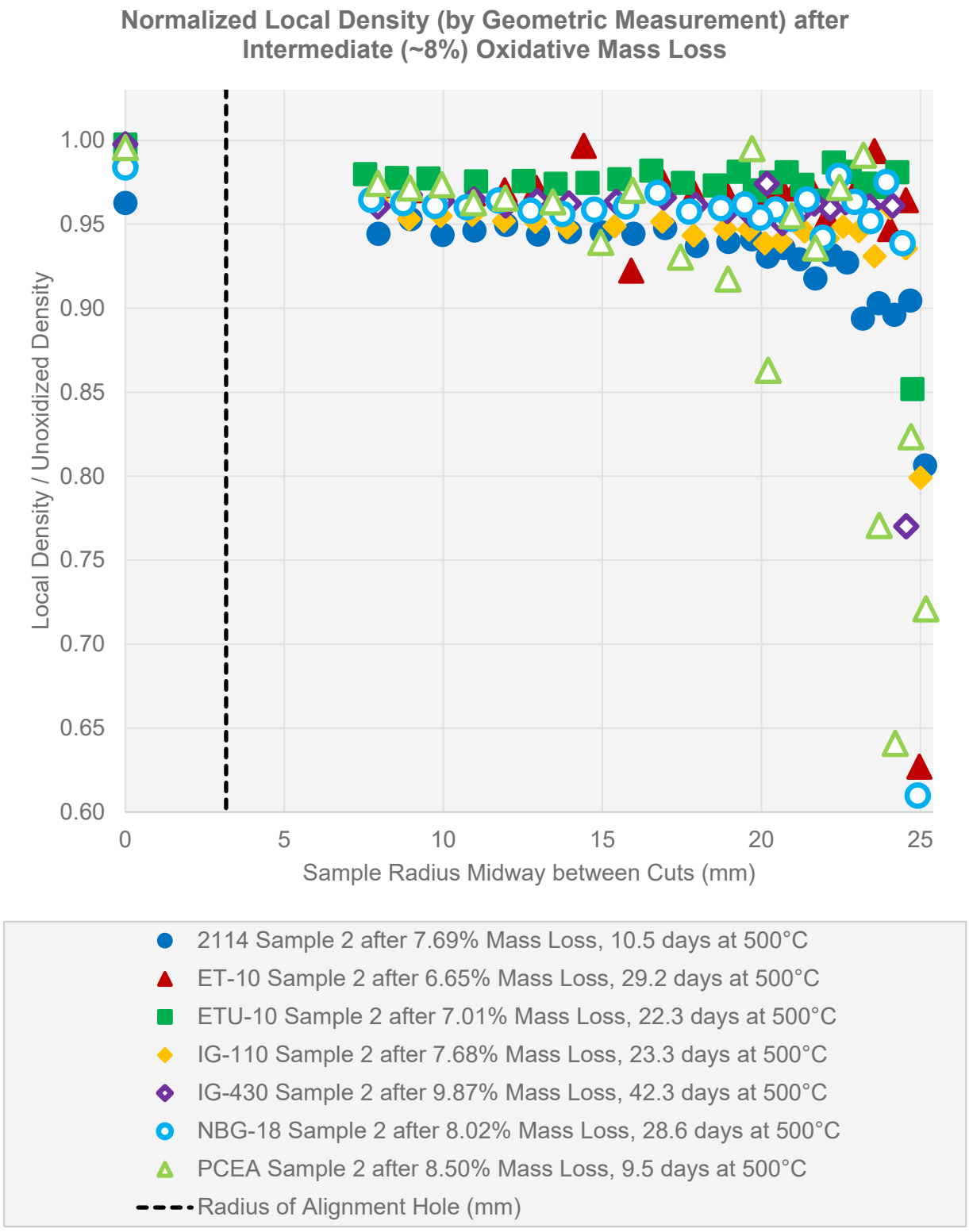

Figure 17. Local density profile (determined by geometric analysis) with sample radius for intermediate mass loss samples for seven grades of graphite normalized by the density of the unoxidized sample. Adjacent cuts were combined to avoid apparent local densities greater than that of the unoxidized sample. Does not include data beyond Cut 24.

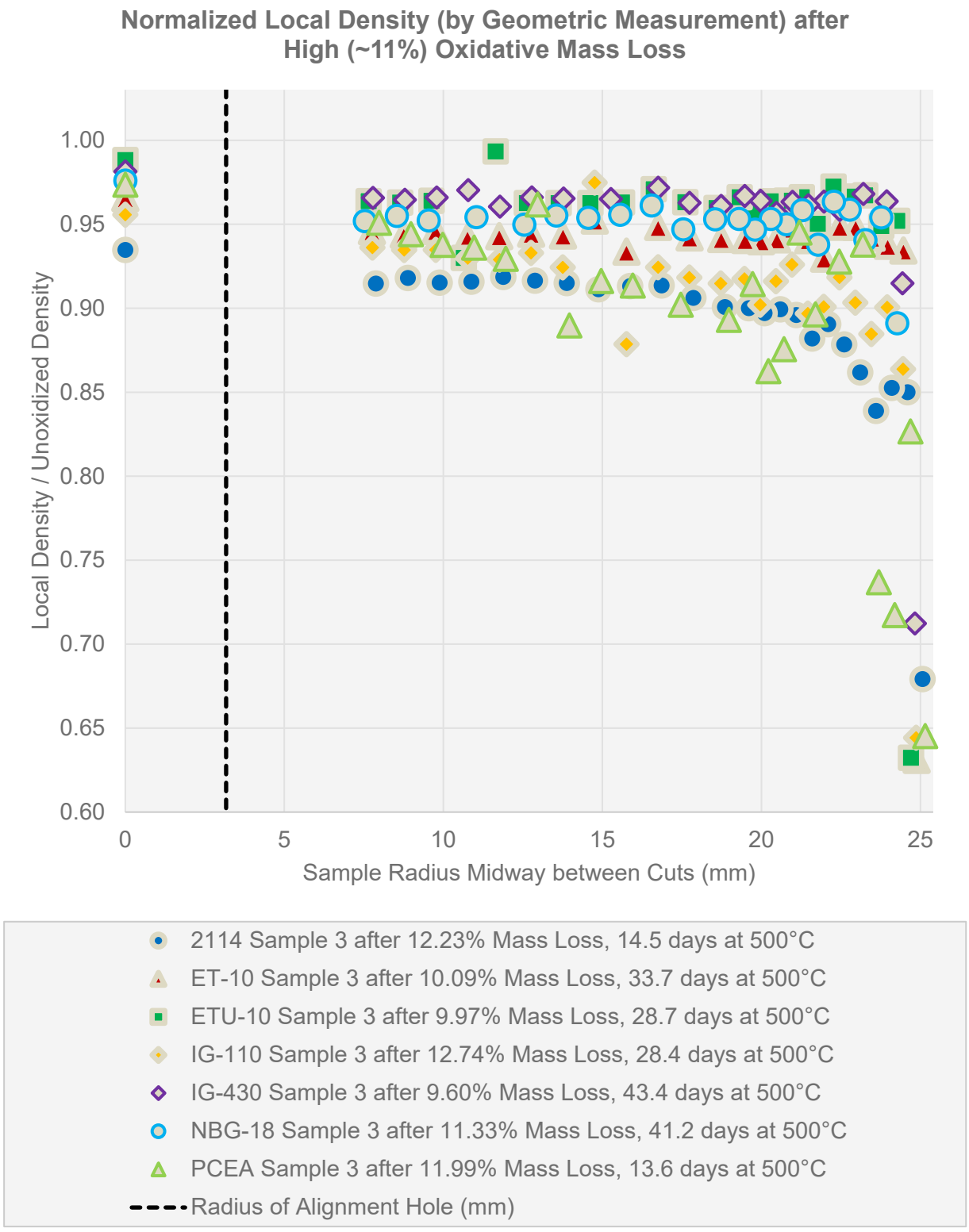

Figure 18. Local density profile (determined by geometric analysis) with sample radius for high-mass-loss samples for seven grades of graphite normalized by the density of the unoxidized sample. Adjacent cuts were combined to avoid apparent local densities greater than that of the unoxidized sample. Does not include data beyond Cut 24.

6. CONCLUSIONS

This work generated a large body of data examining 21 graphite samples through more than 26 lathing steps each. Graphically these data provide a qualitative view of the density evolution with oxidation for each of the grades tested. Because each sample represents the behavior of a single grade after a single level of oxidative mass loss, these data are only a quantitative measure of the penetration depth for a single test case each. The one near-duplicate repetition that fortuitously occurred (for the intermediate- and high-mass-loss levels for IG-430) does indicate very good conformance (reproducibility) among measurement and handling practices for repetition of a given test case. Consider, however, that this reproducibility may vary grade-to-grade depending on the microstructural uniformity inherent to each fabrication process. For a statistical measure of the uncertainties in these density determinations, stepwise lathing of multiple unoxidized and similarly oxidized (duplicate) samples of each grade would be necessary.

Given the magnitude of the defined scope, this study provides an excellent benchmark for the extent of oxidation penetration for the seven grades tested. That significant mass loss occurs at the exterior of samples at as low an isothermal oxidation temperature as these samples experienced (500°C) is particularly noteworthy. This is an important practical limitation to achieving uniform oxidation under actual experimental conditions. While relatively flat density profiles were generally observed beyond the first few cuts, significant differences were among the grades demonstrating important differences likely to affect post-oxidation performance (mechanical or thermal). Likewise, evaluation of post-oxidation performance should be expected to require long-duration high-mass-loss oxidation to achieve a uniformly oxidized residual sample to represent uniform mass loss at levels where the core of such a sample could be objectively asserted to be representative of uniform oxidation in the bulk. Additional post-oxidation preparation to remove the (density gradient) surface may also be advisable to achieve the uniform oxidative mass loss to satisfy the intent of the ASME Code. Mathematical treatment of the local oxidation will require additional assumptions to account for the aggregation of deviations in measurement, without arbitrarily discounting the potential for highly localized internal oxidation damage.

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Appendix A

Tabular Data for Each Grade and Each Machining Step

Table A-1. Measured data for low-oxidation mass-loss sample (Sample 1) of graphite grade 2114.

2114 Sample 1 after 3.58% Mass Loss, 5.7 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	93.61266	5.085	2.548		
After Oxidation	90.25708	5.08	2.548		
Faced	87.92286		2.474		
With Alignment Hole	86.52224	5.08	2.474		
Before First Cut	86.52074	5.08	2.474		
Cut 1	83.46592	4.984	2.474	43.6895	91.192
Cut 2	80.07524	4.882	2.474	41.8643	87.479
Cut 3	76.94322	4.785	2.477	40.2735	83.9294
Cut 4	73.79494	4.686	2.474	38.6287	80.4561
Cut 5	70.64674	4.585	2.474	36.9544	76.9604
Cut 6	67.58454	4.486	2.475	35.3161	73.5879
Cut 7	64.57458	4.387	2.474	33.7925	70.3362
Cut 8	61.70396	4.289	2.474	32.2235	67.1356
Cut 9	58.85197	4.191	2.473	30.7584	64.0254
Cut 10	56.08547	4.093	2.473	29.3399	61.0573
Cut 11	53.41716	3.996	2.474	27.8841	58.1379
Cut 12	50.74663	3.898	2.473	26.5646	55.2231
Cut 13	45.60902	3.7	2.473	23.8429	49.6301
Cut 14	40.79262	3.505	2.473	21.3308	44.4059
Cut 15	36.08794	3.304	2.473	18.9257	39.2633
Cut 16	31.70285	3.105	2.473	16.5773	34.4687
Cut 17	27.56389	2.904	2.473	14.3749	29.9858
Cut 18	23.77646	2.708	2.473	12.3981	25.8675
Cut 19	20.21541	2.508	2.473	10.5432	22.0035
Cut 20	16.88614	2.307	2.473	8.8321	18.3542
Cut 21	13.85709	2.108	2.473	7.3262	15.1367
Cut 22	11.11198	1.908	2.473	5.7759	12.096
Cut 23	8.60244	1.706	2.472	4.4541	9.3477
Cut 24	6.3908	1.505	2.472	3.3568	6.9986
Cut 25	4.43852	1.304	2.473	2.3069	4.8746
Cut 26	2.78148	1.104	2.472	1.4398	3.0418
Cut 27	1.40322	0.903	2.472	0.7555	1.5686
Core (by difference with Alignment Hole)	1.40062	0.634			

Table A-2. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade 2114.

2114 Sample 2 after 7.69% Mass Loss, 10.5 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	93.64000	5.084	2.5455		
After Oxidation	86.4414	5.073	2.5455		
Faced	83.87112		2.463		
With Alignment Hole	82.51536	5.073	2.463		
Before First Cut	82.51296	5.073	2.463		
Cut 1	80.01216	4.985	2.463	42.1828	89.4329
Cut 2	76.91486	4.886	2.463	40.4818	85.7704
Cut 3	73.878	4.786	2.463	38.8676	82.29
Cut 4	70.94062	4.688	2.463	37.3425	78.8757
Cut 5	68.03562	4.588	2.463	35.7596	75.6427
Cut 6	65.11614	4.489	2.463	34.1506	72.276
Cut 7	62.24636	4.39	2.463	32.7389	69.0982
Cut 8	59.40025	4.288	2.462	31.2125	65.9133
Cut 9	56.66814	4.189	2.462	29.7849	62.8725
Cut 10	53.95382	4.089	2.462	28.3593	59.8291
Cut 11	51.37159	3.991	2.462	27.0026	56.9496
Cut 12	48.77297	3.891	2.462	25.7056	54.1035
Cut 13	43.85432	3.694	2.462	23.0521	48.588
Cut 14	39.13435	3.494	2.462	20.6236	43.4333
Cut 15	34.6482	3.295	2.462	18.2745	38.4067
Cut 16	30.41981	3.095	2.462	15.8842	33.6736
Cut 17	26.45229	2.895	2.462	13.8659	29.2724
Cut 18	22.767	2.696	2.462	11.9234	25.1872
Cut 19	19.31639	2.495	2.462	10.0442	21.3823
Cut 20	16.12899	2.295	2.462	8.4836	17.8491
Cut 21	13.2179	2.095	2.462	6.9106	14.6278
Cut 22	10.56689	1.894	2.461	5.5215	11.668
Cut 23	8.15947	1.693	2.461	4.2561	9.0255
Cut 24	6.0315	1.491	2.461	3.1661	6.6912
Cut 25	4.16624	1.29	2.461	2.1578	4.5917
Cut 26	2.58505	1.089	2.46	1.3391	2.8718
Cut 27	1.28699	0.891	2.46	0.6752	1.3606
Core (by difference with Alignment Hole)	1.35576	0.634			

Table A-3. Measured data for the high-oxidation mass-loss sample (Sample 3) of graphite grade 2114.

2114 Sample 3 after 12.23% Mass Loss, 14.5 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	93.90838	5.0845	2.555		
After Oxidation	82.42746	5.057	2.555		
Faced	79.91436		2.468		
With Alignment Hole	78.5964	5.057	2.468		
Before First Cut	78.59468	5.057	2.468		
Cut 1	76.46892	4.968	2.468	40.6231	87.5845
Cut 2	73.56516	4.869	2.468	38.8924	83.9975
Cut 3	70.71124	4.77	2.467	37.3984	80.5694
Cut 4	67.93326	4.67	2.468	35.9404	77.2799
Cut 5	65.1677	4.571	2.468	34.3842	73.9964
Cut 6	62.32658	4.469	2.468	32.4465	70.3101
Cut 7	59.56586	4.369	2.468	31.323	67.5046
Cut 8	56.89341	4.269	2.468	29.826	64.3961
Cut 9	54.21522	4.168	2.467	28.5817	61.3651
Cut 10	51.64266	4.069	2.467	27.1949	58.4183
Cut 11	49.1382	3.97	2.467	25.9301	55.6297
Cut 12	46.66306	3.87	2.467	24.6564	52.7941
Cut 13	41.89872	3.67	2.467	22.0452	47.2954
Cut 14	37.40364	3.472	2.467	19.6541	42.2024
Cut 15	33.08115	3.272	2.467	17.4881	37.3529
Cut 16	29.07597	3.075	2.467	15.317	32.7878
Cut 17	25.27211	2.875	2.467	13.1754	28.4639
Cut 18	21.70934	2.675	2.467	11.3497	24.4265
Cut 19	18.41423	2.476	2.467	9.676	20.7071
Cut 20	15.35166	2.276	2.467	8.0585	17.2806
Cut 21	12.55557	2.076	2.466	6.5414	13.9911
Cut 22	10.03019	1.877	2.466	5.2087	11.2704
Cut 23	7.73048	1.676	2.466	4.0286	8.5738
Cut 24	5.68894	1.474	2.466	2.962	6.4069
Cut 25	3.90547	1.274	2.466	2.0696	4.4083
Cut 26	2.39936	1.074	2.465	1.2711	2.7332
Core (by difference with Alignment Hole)	1.31796	0.634			

Table A- 4. Measured data for low-oxidation mass-loss sample (Sample 1) of graphite grade ET-10.

ET-10 Sample 1 after 1.95% Mass Loss, 11.0 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	92.06692	5.082666667	2.5425		
After Oxidation	90.26856	5.0724375	2.5425		
Faced	88.76126		2.495975		
With Alignment Hole	87.3415	5.0724375	2.496175		
Before First Cut	87.33944	5.0724375	2.496175		
Cut 1	84.96174	4.9896	2.496675	44.4698	92.351
Cut 2	81.59942	4.891675	2.496575	42.4189	88.5559
Cut 3	78.71526	4.7947125	2.4964	40.8256	85.0753
Cut 4	75.04272	4.69485	2.496475	38.9853	81.3913
Cut 5	71.85324	4.5942875	2.4964	37.47	77.9649
Cut 6	68.64396	4.4950375	2.4959	35.6491	74.4291
Cut 7	65.58186	4.394775	2.495925	34.1313	71.1788
Cut 8	62.54966	4.2941625	2.496075	32.6324	67.9377
Cut 9	59.6617	4.1960375	2.49575	31.0289	64.703
Cut 10	56.83088	4.0978875	2.4955	29.6727	61.7798
Cut 11	54.08981	4.0000375	2.496025	28.2151	58.7655
Cut 12	51.34716	3.90005	2.4956	26.7428	55.7449
Cut 13	46.17472	3.703575	2.495375	24.0126	50.1106
Cut 14	41.37921	3.506675	2.495625	21.4955	44.8597
Cut 15	36.5271	3.3074375	2.4957	19.0685	39.6604
Cut 16	32.66681	3.1080875	2.4955	16.7005	34.8328
Cut 17	27.91072	2.9078125	2.495225	14.4925	30.2939
Cut 18	24.02209	2.7079	2.495375	12.5147	26.1153
Cut 19	20.4188	2.5087625	2.49525	10.6196	22.1629
Cut 20	17.10524	2.310425	2.4952	8.8891	18.5734
Cut 21	14.04419	2.110675	2.4951	7.3372	15.3302
Cut 22	11.29322	1.91375	2.495325	5.9056	12.2869
Cut 23	8.7881	1.71455	2.49465	4.5922	9.5688
Cut 24	6.54635	1.5147	2.494525	3.4737	7.1418
Cut 25	4.58284	1.314525	2.494675	2.367	4.9897
Cut 26	2.88899	1.11345	2.494525	1.537	3.1728
Cut 27	1.49186	0.915025	2.50015	0.7696	1.6348
Core (by difference with Alignment Hole)	1.41976	0.634			

Table A-5. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade ET-10.

ET-10 Sample 2 after 6.65% Mass Loss, 29.2 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	92.17142	5.084333333	2.5435		
After Oxidation	86.0407	5.0278625	2.5435		
Faced	84.14334		2.4713		
With Alignment Hole	82.7632	5.0278625	2.471425		
Before First Cut	82.76	5.0278625	2.471425		
Cut 1	81.2589	4.95865	2.47155	42.7708	89.6624
Cut 2	77.95986	4.858025	2.47145	40.9539	85.914
Cut 3	74.8748	4.76025	2.47145	39.2921	82.4184
Cut 4	71.6159	4.6597125	2.471675	37.4177	78.7354
Cut 5	68.50152	4.55955	2.47135	35.8034	75.367
Cut 6	65.53702	4.4629375	2.47095	34.2435	72.0494
Cut 7	62.60646	4.3624875	2.4709	32.7563	68.9072
Cut 8	59.79619	4.265625	2.471075	31.3536	65.8742
Cut 9	57.05889	4.1691625	2.470675	29.8079	62.7702
Cut 10	54.40972	4.0736875	2.470575	28.4903	59.9329
Cut 11	51.73411	3.9745125	2.47085	27.1789	57.0127
Cut 12	49.07902	3.8737	2.47045	25.7947	54.0518
Cut 13	44.02609	3.674325	2.470075	23.0218	48.4183
Cut 14	39.31432	3.47795	2.470525	20.6243	43.2909
Cut 15	34.83266	3.2816125	2.4706	18.3619	38.4065
Cut 16	30.75522	3.0810125	2.470175	16.0291	33.648
Cut 17	26.57538	2.883125	2.470325	13.9495	29.2638
Cut 18	22.8615	2.6843625	2.4701	11.9979	25.1666
Cut 19	19.3922	2.4849125	2.46995	10.2254	21.3952
Cut 20	16.19311	2.2853375	2.469975	8.4865	17.8164
Cut 21	13.23789	2.08365	2.4698	6.9241	14.4568
Cut 22	10.58779	1.8853625	2.469925	5.5547	11.6828
Cut 23	8.17913	1.684575	2.4692	4.3187	9.0202
Cut 24	6.04314	1.484625	2.469175	3.195	6.6778
Cut 25	4.16021	1.2815375	2.4691	2.1826	4.6008
Cut 26	2.56472	1.0812625	2.4687	1.3494	2.8387
Core (by difference with Alignment Hole)	1.38014	0.634			

Table A-6. Measured data for high-oxidation mass-loss sample (Sample 3) of graphite grade ET-10.

ET-10 Sample 3 after 10.09% Mass Loss, 33.7 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	92.16814	5.082833333	2.542		
After Oxidation	82.86448	5.009975	2.542		
Faced	80.54712		2.447825		
With Alignment Hole	79.21428	5.009975	2.448175		
Before First Cut	79.21148	5.009975	2.448175		
Cut 1	77.74546	4.9420125	2.4479	41.1618	87.2585
Cut 2	74.66658	4.843975	2.447925	39.3474	83.6474
Cut 3	71.58446	4.7441	2.4478	37.7551	80.2197
Cut 4	68.48064	4.6418875	2.44785	35.8471	76.5023
Cut 5	65.50842	4.5425375	2.447725	34.4022	73.2778
Cut 6	62.60276	4.443275	2.44775	32.8021	69.9309
Cut 7	59.83192	4.3445125	2.44775	31.3577	66.8612
Cut 8	57.08235	4.245425	2.447625	30.099	63.8802
Cut 9	54.38192	4.146525	2.447475	28.6201	60.8105
Cut 10	51.76641	4.0477625	2.44705	27.2989	57.9861
Cut 11	49.16787	3.947075	2.447775	25.8163	54.971
Cut 12	46.64607	3.846925	2.447225	24.5482	52.126
Cut 13	41.81902	3.6476875	2.4471	22.0754	46.8123
Cut 14	37.26136	3.4492125	2.446825	19.6436	41.7877
Cut 15	32.9331	3.2509	2.447075	17.3566	36.8638
Cut 16	28.91807	3.0522625	2.446825	15.1694	32.3971
Cut 17	25.04831	2.85185	2.447175	13.0847	28.0011
Cut 18	21.48968	2.6522875	2.446675	11.3535	24.0818
Cut 19	18.16102	2.4511875	2.446625	9.5628	20.3135
Cut 20	15.11821	2.251375	2.446475	7.9854	16.9346
Cut 21	12.34373	2.052125	2.446475	6.6299	13.8566
Cut 22	9.78996	1.8507375	2.446575	5.1257	10.9813
Cut 23	7.5277	1.65145	2.4457	3.9672	8.4378
Cut 24	5.49722	1.4499125	2.445775	2.9025	6.1728
Cut 25	3.73968	1.2485125	2.445525	1.951	4.1712
Cut 26	2.25171	1.0492625	2.444975	1.1687	2.5241
Core (by difference with Alignment Hole)	1.33284	0.634			

Table A-7. Measured data for low-oxidation mass-loss sample (Sample 1) of graphite grade ETU-10.

ETU-10 Sample 1 after 1.97% Mass Loss, 9.4 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	89.8403	5.0895	2.54225		
After Oxidation	88.06682	5.0690125	2.54225		
Faced	86.60342		2.493175		
With Alignment Hole	85.21784	5.0690125	2.49395		
Before First Cut	85.21388	5.0690125	2.49395		
Cut 1	82.27274	4.972025	2.493825	42.8256	90.5252
Cut 2	78.8503	4.869825	2.4976	41.2543	86.8292
Cut 3	75.70622	4.7731375	2.493775	39.4523	83.3033
Cut 4	72.53568	4.6733875	2.493675	37.812	79.7791
Cut 5	69.3817	4.5734	2.4932	36.1131	76.2559
Cut 6	66.36954	4.47585	2.493625	34.6197	73.0086
Cut 7	63.39696	4.37555	2.492925	32.92	69.6005
Cut 8	60.51668	4.277075	2.493325	31.5084	66.5263
Cut 9	57.65051	4.1773125	2.492825	30.069	63.3889
Cut 10	54.86378	4.07705	2.4925	28.6017	60.3001
Cut 11	52.0841	3.9746	2.49295	27.1407	57.2713
Cut 12	49.37439	3.872825	2.492525	25.7663	54.2686
Cut 13	44.36452	3.6759	2.492375	23.1103	48.7418
Cut 14	39.52002	3.4761	2.4924	20.6912	43.5189
Cut 15	34.93129	3.2759	2.49245	18.229	38.3717
Cut 16	30.62851	3.0756625	2.492175	15.9349	33.6264
Cut 17	26.65689	2.878525	2.49225	13.8902	29.311
Cut 18	22.92921	2.680025	2.492	11.9449	25.219
Cut 19	19.43999	2.4803125	2.492175	10.1962	21.4143
Cut 20	16.23158	2.2812	2.492125	8.4416	17.8027
Cut 21	13.26901	2.080275	2.492025	6.9346	14.6138
Cut 22	10.61531	1.8823125	2.49185	5.5232	11.6906
Cut 23	8.19828	1.681825	2.491475	4.2866	9.0251
Cut 24	6.04543	1.481025	2.4915	3.1181	6.6543
Cut 25	4.18041	1.280925	2.49115	2.1675	4.6055
Cut 26	2.57615	1.0812	2.490975	1.363	2.8627
Cut 27	1.25756	0.8823125	2.490525	0.6439	1.4224
Core (by difference with Alignment Hole)	1.38558	0.634			

Table A-8. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade ETU-10.

ETU-10 Sample 2 after 7.01% Mass Loss, 22.3 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	89.51632	5.085666667	2.543		
After Oxidation	83.24184	4.99485	2.543		
Faced	80.27638		2.433075		
With Alignment Hole	78.94918	4.99485	2.433625		
Before First Cut	78.94508	4.99485	2.433625		
Cut 1	76.38228	4.9030375	2.433525	40.0809	85.2301
Cut 2	73.27406	4.8044375	2.432825	38.5898	81.8453
Cut 3	70.26252	4.7060375	2.433275	36.8738	78.4096
Cut 4	67.2225	4.6047875	2.4333	35.2068	74.879
Cut 5	64.23922	4.50395	2.432925	33.58	71.4925
Cut 6	61.41348	4.406875	2.43295	32.1526	68.4415
Cut 7	58.66238	4.3079625	2.4324	30.6102	65.2835
Cut 8	55.91504	4.20785	2.432925	29.2074	62.2956
Cut 9	53.26233	4.1096375	2.4329	27.9017	59.3337
Cut 10	50.62674	4.00905	2.43225	26.5523	56.418
Cut 11	48.0434	3.9074375	2.432225	25.1153	53.5824
Cut 12	45.52011	3.8067375	2.432025	23.8843	50.6962
Cut 13	40.7396	3.60655	2.43185	21.3868	45.3869
Cut 14	36.20608	3.406175	2.4313	19.0729	40.41
Cut 15	31.94817	3.2081375	2.43205	16.7711	35.5658
Cut 16	27.89779	3.0065875	2.431675	14.627	31.0954
Cut 17	24.13963	2.8062	2.431775	12.6455	26.8942
Cut 18	20.6368	2.605475	2.43145	10.8068	22.9705
Cut 19	17.38528	2.40455	2.431675	9.1457	19.4045
Cut 20	14.42751	2.2312	2.431525	7.5775	16.0746
Cut 21	11.71505	2.0065	2.431375	6.1416	13.0667
Cut 22	9.24864	1.80655	2.431525	4.8122	10.2669
Cut 23	7.05415	1.60795	2.430825	3.6961	7.8741
Cut 24	5.10082	1.4082875	2.4308	2.6807	5.6901
Cut 25	3.41675	1.208775	2.43015	1.7817	3.8144
Cut 26	1.97203	1.008025	2.4299	1.0348	2.2103
Core (by difference with Alignment Hole)	1.3272	0.634			

Table A-9. Measured data for high-oxidation mass-loss sample (Sample 3) of graphite grade ETU-10.

ETU-10 Sample 3 after 9.97% Mass Loss, 28.7 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	90.33546	5.088333333	2.543		
After Oxidation	81.32566	4.9767	2.543		
Faced	78.99148		2.443025		
With Alignment Hole	77.66216	4.9767	2.443425		
Before First Cut	77.65922	4.9767	2.443425		
Cut 1	76.11858	4.9030125	2.4431	40.0136	85.3584
Cut 2	73.04346	4.803575	2.442525	38.3695	81.7357
Cut 3	69.99814	4.7027	2.4433	36.6082	78.2574
Cut 4	66.93326	4.600925	2.4433	34.9042	74.7164
Cut 5	64.00474	4.50145	2.443125	33.4065	71.4509
Cut 6	61.17622	4.40385	2.442925	32.0094	68.3619
Cut 7	58.39226	4.3033125	2.4426	30.2122	64.9575
Cut 8	55.6172	4.2024	2.442725	29.0506	62.1375
Cut 9	53.02833	4.1058125	2.4423	27.6656	59.1966
Cut 10	50.51281	4.0097	2.442025	26.5268	56.4836
Cut 11	48.02159	3.9115625	2.4419	25.1158	53.6685
Cut 12	45.58078	3.8138375	2.44185	23.8973	50.9438
Cut 13	40.96396	3.620475	2.4418	21.4661	45.7975
Cut 14	36.46689	3.422375	2.44165	19.1277	40.7908
Cut 15	32.14959	3.2223875	2.441775	16.8527	35.9644
Cut 16	28.13403	3.0228625	2.44155	14.7507	31.4986
Cut 17	24.39581	2.8244125	2.44155	12.7255	27.2778
Cut 18	20.88167	2.6242	2.44145	10.9202	23.3331
Cut 19	17.64929	2.4254875	2.44135	9.2186	19.7194
Cut 20	14.63896	2.231025	2.441275	7.651	16.3439
Cut 21	11.90589	2.024675	2.44115	6.2617	13.3398
Cut 22	9.43244	1.8255375	2.441225	4.901	10.5065
Cut 23	7.24925	1.62945	2.4407	3.7413	8.115
Cut 24	5.28336	1.430225	2.440725	2.7642	5.9257
Cut 25	3.55472	1.2285625	2.4402	1.8507	3.9757
Cut 26	2.09304	1.0276375	2.4398	1.0844	2.3427
Core (by difference with Alignment Hole)	1.32932	0.634			

Table A-10. Measured data for the low-oxidation mass-loss sample (Sample 1) of graphite grade IG-110.

IG-110 Sample 1 after 3.92% Mass Loss, 15.7 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	91.32786	5.082833333	2.56475		
After Oxidation	87.7501	5.061	2.56475		
Faced	84.13854		2.441		
With Alignment Hole	82.78282	5.061	2.441		
Before First Cut	82.7763	5.061	2.441		
Cut 1	80.09286	4.97	2.442	43.0798	89.7073
Cut 2	77.1736	4.87	2.441	41.2809	85.9913
Cut 3	73.68266	4.771	2.441	39.5907	82.4709
Cut 4	70.6507	4.672	2.441	38.0219	79.0796
Cut 5	67.6149	4.572	2.441	36.3906	75.7383
Cut 6	64.6755	4.474	2.44	34.7148	72.261
Cut 7	61.79816	4.374	2.441	33.3284	69.2225
Cut 8	59.48861	4.275	2.441	31.8639	66.0978
Cut 9	56.16146	4.174	2.441	30.3931	62.9859
Cut 10	53.45403	4.075	2.44	29.0037	59.9066
Cut 11	-999	3.974	2.441	27.5075	56.984
Cut 12	48.24173	3.875	2.44	26.0335	54.0132
Cut 13	43.37718	3.68	2.44	23.4661	48.5722
Cut 14	38.75929	3.483	2.44	20.9862	43.4186
Cut 15	34.26619	3.283	2.44	18.5857	38.405
Cut 16	30.39438	3.083	2.44	16.2819	33.6917
Cut 17	26.12089	2.883	2.44	14.1287	29.2875
Cut 18	22.45437	2.683	2.44	12.0842	25.1359
Cut 19	19.05105	2.484	2.44	10.3123	21.3788
Cut 20	15.99396	2.29	2.44	8.6961	17.9499
Cut 21	13.1113	2.091	2.44	7.0971	14.616
Cut 22	10.5269	1.895	2.44	5.7305	11.828
Cut 23	8.17593	1.697	2.439	4.371	9.1612
Cut 24	6.05002	1.496	2.439	3.2782	6.8096
Cut 25	4.21284	1.296	2.439	2.2814	4.7296
Cut 26	2.61772	1.095	2.438	1.4019	2.9428
Cut 27	1.30429	0.895	2.438	0.6909	1.4721
Core (by difference with Alignment Hole)	1.35572	0.634			

Table A-11. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade IG-110.

IG-110 Sample 2 after 7.68% Mass Loss, 23.3 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	91.95164	5.082666667	2.56025		
After Oxidation	84.89426	5.042	2.56025		
Faced	81.40864		2.44		
With Alignment Hole	80.0617	5.042	2.441		
Before First Cut	80.05604	5.042	2.441		
Cut 1	77.8063	4.959	2.441	42.2762	88.6552
Cut 2	74.66022	4.858	2.441	40.4064	84.9942
Cut 3	71.62312	4.761	2.441	38.9281	81.5746
Cut 4	68.67762	4.662	2.44	37.4024	78.2836
Cut 5	65.7185	4.562	2.44	35.726	74.7593
Cut 6	62.93012	4.466	2.44	33.9908	71.4039
Cut 7	60.2212	4.37	2.44	32.7268	68.5312
Cut 8	57.74346	4.271	2.44	31.2499	65.4539
Cut 9	54.79641	4.172	2.44	29.9512	62.4055
Cut 10	52.14304	4.071	2.44	28.4534	59.4175
Cut 11	49.6082	3.972	2.44	27.0641	56.5144
Cut 12	47.11438	3.873	2.439	25.6505	53.6
Cut 13	42.26617	3.673	2.439	23.1199	48.1439
Cut 14	37.73782	3.475	2.439	20.6514	42.9873
Cut 15	33.4232	3.277	2.44	18.2885	38.0321
Cut 16	29.6569	3.078	2.439	16.0017	33.417
Cut 17	25.50174	2.877	2.439	13.9293	28.9915
Cut 18	21.94745	2.678	2.439	11.907	24.9013
Cut 19	18.65181	2.48	2.439	10.1732	21.1815
Cut 20	15.59316	2.281	2.439	8.5258	17.7192
Cut 21	12.77915	2.082	2.438	7.0538	14.5783
Cut 22	10.23586	1.884	2.439	5.5926	11.6337
Cut 23	7.92927	1.684	2.438	4.3301	8.9972
Cut 24	5.86776	1.485	2.438	3.2208	6.6643
Cut 25	4.05245	1.283	2.438	2.23	4.6392
Cut 26	2.51279	1.084	2.438	1.3955	2.8836
Cut 27	1.23943	0.886	2.437	0.677	1.4379
Core (by difference with Alignment Hole)	1.34694	0.634			

Table A-12. Measured data for high-oxidation mass-loss sample (Sample 3) of graphite grade IG-110.

IG-110 Sample 3 after 12.74% Mass Loss, 28.4 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	91.5929	5.0835	2.55875		
After Oxidation	79.92594	5.005	2.55875		
Faced	76.26554		2.415		
With Alignment Hole	74.98108	5.005	2.415		
Before First Cut	74.97692	5.005	2.415		
Cut 1	73.60578	4.941	2.416	40.2065	85.6553
Cut 2	70.75276	4.84	2.415	38.6283	82.2311
Cut 3	67.89668	4.741	2.415	37.0408	78.845
Cut 4	65.12148	4.641	2.415	35.5243	75.6077
Cut 5	62.3208	4.54	2.414	33.8559	72.1673
Cut 6	59.59056	4.441	2.414	32.272	68.8654
Cut 7	56.94547	4.341	2.415	31.0101	65.9735
Cut 8	54.39742	4.242	2.415	29.632	62.9699
Cut 9	51.77591	4.141	2.414	28.2003	59.9604
Cut 10	49.29443	4.042	2.414	26.9359	57.0994
Cut 11	46.91015	3.943	2.414	25.6509	54.3655
Cut 12	44.54517	3.844	2.414	24.2898	51.5068
Cut 13	39.96471	3.644	2.414	21.8662	46.2429
Cut 14	35.71785	3.449	2.413	19.5602	41.2986
Cut 15	31.63759	3.252	2.414	17.3341	36.5756
Cut 16	27.91589	3.051	2.413	15.1604	32.0328
Cut 17	24.06845	2.851	2.413	13.1653	27.813
Cut 18	20.65109	2.65	2.413	11.2548	23.8558
Cut 19	17.49992	2.452	2.413	9.53	20.0682
Cut 20	14.60562	2.254	2.413	7.9981	16.8475
Cut 21	11.90139	2.052	2.412	6.512	13.7292
Cut 22	9.47256	1.853	2.413	5.1153	10.9054
Cut 23	7.28117	1.653	2.412	3.9845	8.3929
Cut 24	5.34591	1.454	2.412	2.9275	6.1699
Cut 25	3.64661	1.253	2.411	1.9894	4.2155
Cut 26	2.19637	1.052	2.411	1.1754	2.5248
Core (by difference with Alignment Hole)	1.28446	0.634			

Table A-13. Measured data for low-oxidation mass-loss sample (Sample 1) of graphite grade IG-430.

IG-430 Sample 1 after 3.48% Mass Loss, 26.3 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	92.72014	5.084833333	2.55375		
After Oxidation	89.48992	5.05	2.55375		
Faced	86.76376		2.449		
With Alignment Hole	85.35674	5.05	2.449		
Before First Cut	85.35218	5.05	2.449		
Cut 1	83.45516	4.983	2.45	44.484	91.4693
Cut 2	80.7408	4.885	2.449	42.6933	87.752
Cut 3	76.92108	4.786	2.449	40.9564	84.306
Cut 4	74.1106	4.687	2.449	39.0878	80.5464
Cut 5	70.57272	4.588	2.449	37.2811	76.9685
Cut 6	67.50242	4.489	2.449	35.8175	73.7547
Cut 7	64.56464	4.392	2.449	34.2808	70.6025
Cut 8	61.65218	4.294	2.45	32.7832	67.4743
Cut 9	58.72176	4.193	2.449	31.1024	64.1266
Cut 10	55.95349	4.095	2.449	29.7552	61.1891
Cut 11	53.48156	3.995	2.448	28.2665	58.1759
Cut 12	50.61786	3.896	2.449	26.9331	55.2902
Cut 13	45.33853	3.696	2.448	24.115	49.5766
Cut 14	40.45321	3.497	2.448	21.5025	44.238
Cut 15	35.8376	3.299	2.449	19.0592	39.1979
Cut 16	32.16376	3.099	2.449	16.7054	34.4348
Cut 17	27.39051	2.901	2.448	14.6414	30.0356
Cut 18	23.58838	2.702	2.448	12.5317	25.8245
Cut 19	20.07883	2.505	2.448	10.725	22.0138
Cut 20	16.79434	2.306	2.448	8.9419	18.3634
Cut 21	13.77659	2.106	2.448	7.3378	15.0869
Cut 22	11.04895	1.907	2.448	5.8237	12.0886
Cut 23	8.56997	1.707	2.447	4.6271	9.4769
Cut 24	6.37442	1.506	2.447	3.4037	7.0003
Cut 25	4.4355	1.305	2.447	2.3606	4.8666
Cut 26	2.78072	1.104	2.446	1.4634	3.0482
Cut 27	1.4254	0.907	2.446	0.6974	1.6255
Core (by difference with Alignment Hole)	1.40702	0.634			

Table A-14. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade IG-430.

IG-430 Sample 2 after 9.87% Mass Loss, 42.3 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	92.36864	5.088166667	2.54625		
After Oxidation	83.25538	4.984	2.54625		
Faced	79.92112		2.416		
With Alignment Hole	78.56438	4.984	2.415		
Before First Cut	78.5626	4.984	2.416		
Cut 1	77.97472	4.952	2.416	42.1199	87.2548
Cut 2	75.85064	4.869	2.416	40.7442	84.9877
Cut 3	73.02724	4.779	2.416	39.3185	81.9389
Cut 4	70.09966	4.678	2.415	37.6218	78.288
Cut 5	66.91452	4.578	2.415	35.8071	74.7942
Cut 6	64.02202	4.48	2.415	34.4361	71.7318
Cut 7	61.20326	4.382	2.415	32.9375	68.5588
Cut 8	58.41011	4.283	2.415	31.486	65.4897
Cut 9	55.67087	4.183	2.415	29.9876	62.3913
Cut 10	53.012	4.083	2.415	28.6209	59.4472
Cut 11	50.40601	3.985	2.415	27.1744	56.4865
Cut 12	47.86135	3.885	2.415	25.9235	53.7196
Cut 13	42.97836	3.686	2.414	23.2724	48.2545
Cut 14	38.33522	3.487	2.414	20.8108	43.0703
Cut 15	33.90762	3.287	2.414	18.2419	38.0073
Cut 16	29.97391	3.089	2.414	16.1721	33.4842
Cut 17	25.89518	2.889	2.414	14.0577	29.0893
Cut 18	22.26295	2.689	2.414	12.0018	24.9488
Cut 19	18.91813	2.491	2.414	10.2455	21.2316
Cut 20	15.80801	2.291	2.414	8.5772	17.7683
Cut 21	12.96095	2.092	2.414	7.0003	14.5687
Cut 22	10.33782	1.89	2.414	5.5802	11.5841
Cut 23	7.98315	1.689	2.413	4.3541	8.9898
Cut 24	5.89803	1.487	2.413	3.1867	6.6468
Cut 25	4.07638	1.287	2.413	2.1935	4.5802
Cut 26	2.51847	1.085	2.413	1.3674	2.8227
Cut 27	1.23101	0.886	2.411	0.6786	1.4101
Core (by difference with Alignment Hole)	1.35674	0.634			

Table A-15. Measured data for high-oxidation mass-loss sample (Sample 3) of graphite grade IG-430.

IG-430 Sample 3 after 9.60% Mass Loss, 43.4 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	93.08144	5.089	2.55375		
After Oxidation	84.14938	5.089	2.55375		
Faced	81.0705		2.414		
With Alignment Hole	79.73064	4.994	2.414		
Before First Cut	79.72812	4.994	2.414		
Cut 1	78.33474	4.936	2.414	42.0117	87.2989
Cut 2	75.32832	4.837	2.414	40.6841	83.9824
Cut 3	72.25678	4.739	2.414	38.8397	80.6602
Cut 4	69.36224	4.638	2.414	37.216	77.1663
Cut 5	66.2451	4.542	2.414	35.441	73.7371
Cut 6	63.32028	4.442	2.414	34.0929	70.7373
Cut 7	60.5309	4.345	2.414	32.5704	67.5811
Cut 8	57.75382	4.246	2.414	31.1872	64.5647
Cut 9	54.98086	4.145	2.414	29.5246	61.3471
Cut 10	52.31949	4.045	2.414	28.179	58.3567
Cut 11	49.70356	3.945	2.413	26.7305	55.4534
Cut 12	47.17063	3.846	2.413	25.4842	52.6691
Cut 13	42.30405	3.647	2.413	22.8362	47.286
Cut 14	37.70958	3.449	2.413	20.4122	42.1496
Cut 15	33.35256	3.252	2.413	18.0802	37.3344
Cut 16	29.44598	3.053	2.413	15.8414	32.7237
Cut 17	25.40595	2.855	2.413	13.6839	28.3433
Cut 18	21.81019	2.656	2.413	11.7627	24.3612
Cut 19	18.47174	2.457	2.413	9.9863	20.6502
Cut 20	15.36668	2.255	2.413	8.3494	17.1477
Cut 21	12.553	2.057	2.413	6.7642	14.0291
Cut 22	10.0092	1.859	2.412	5.4007	11.1849
Cut 23	7.68232	1.657	2.412	4.131	8.5779
Cut 24	5.63953	1.457	2.412	3.025	6.2963
Cut 25	3.85074	1.257	2.412	2.0953	4.348
Cut 26	2.33552	1.057	2.411	1.248	2.6404
Core (by difference with Alignment Hole)	1.33986	0.634			

Table A-16. Measured data for low-oxidation mass-loss sample (Sample 1) of graphite grade NBG-18.

NBG-18 Sample 1 after 3.86% Mass Loss, 15.7 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	95.41644	5.0875	2.5475		
After Oxidation	91.73358	5.063	2.5475		
Faced	89.06654		2.45785		
With Alignment Hole	87.63458	5.0632125	2.461		
Before First Cut	87.6311	5.0632125	2.461		
Cut 1	84.93344	4.967	2.458	42.59	89.4246
Cut 2	81.4903	4.866	2.459	41.0032	85.9371
Cut 3	78.10054	4.767	2.458	39.4477	82.4624
Cut 4	74.79878	4.666	2.461	37.7756	78.976
Cut 5	71.60434	4.568	2.458	36.1462	75.551
Cut 6	68.409	4.468	2.459	34.4163	72.0646
Cut 7	65.3742	4.369	2.458	33.1079	69.0313
Cut 8	62.37088	4.27	2.458	31.624	65.9411
Cut 9	59.4288	4.171	2.457	30.1612	62.8406
Cut 10	56.59329	4.072	2.458	28.697	59.81
Cut 11	53.86972	3.974	2.458	27.2537	56.8163
Cut 12	51.10831	3.874	2.458	25.9039	53.9582
Cut 13	45.85472	3.675	2.457	23.2584	48.4576
Cut 14	40.92226	3.477	2.458	20.7612	43.2519
Cut 15	36.20297	3.279	2.457	18.3264	38.223
Cut 16	31.74072	3.079	2.458	16.0911	33.5582
Cut 17	27.5468	2.877	2.458	13.9623	29.0976
Cut 18	23.66048	2.676	2.457	12.0082	24.9923
Cut 19	20.07876	2.477	2.457	10.1635	21.1965
Cut 20	16.73659	2.277	2.457	8.4902	17.6935
Cut 21	13.71006	2.078	2.457	7.0811	14.5314
Cut 22	10.95589	1.879	2.457	5.6312	11.5949
Cut 23	8.44573	1.678	2.457	4.2867	8.8915
Cut 24	6.22824	1.478	2.456	3.1479	6.5847
Cut 25	4.27214	1.276	2.456	2.148	4.474
Cut 26	2.62561	1.076	2.456	1.3249	2.7782
Core (by difference with Alignment Hole)	1.43196	0.634			

Table A-17. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade NBG-18.

NBG-18 Sample 2 after 8.02% Mass Loss, 28.6 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	95.44034	5.086	2.54125		
After Oxidation	87.78954	5.026	2.54125		
Faced	85.20194		2.450825		
With Alignment Hole	83.79478	5.0258125	2.451675		
Before First Cut	83.78994	5.0258125	2.451675		
Cut 1	81.89534	4.9381875	2.4517	41.4952	87.5338
Cut 2	78.50764	4.8344125	2.451825	39.9837	84.0475
Cut 3	75.23954	4.736	2.451225	38.308	80.5354
Cut 4	72.03456	4.635025	2.451225	36.6978	77.1812
Cut 5	68.90902	4.5356	2.4514	35.2014	73.8107
Cut 6	65.7986	4.436075	2.4515	33.5144	70.4712
Cut 7	62.81076	4.3344375	2.4511	32.1384	67.4011
Cut 8	59.93621	4.23675	2.45095	30.606	64.2165
Cut 9	57.12566	4.1378125	2.4507	29.091	61.1951
Cut 10	54.39447	4.039925	2.4507	27.7874	58.2782
Cut 11	51.76366	3.9428375	2.45135	26.4316	55.4849
Cut 12	49.14578	3.8446125	2.4508	24.9587	52.4942
Cut 13	44.02551	3.6444	2.450425	22.5141	47.133
Cut 14	39.24249	3.446425	2.450525	19.8907	41.9876
Cut 15	34.66528	3.248075	2.450425	17.6855	37.11
Cut 16	30.35704	3.0478875	2.45045	15.4492	32.4573
Cut 17	26.31824	2.84705	2.450525	13.4671	28.1764
Cut 18	22.60476	2.6484375	2.45065	11.545	24.1997
Cut 19	19.0915	2.4461625	2.45035	9.748	20.4091
Cut 20	15.873	2.24625	2.450025	8.103	16.9275
Cut 21	12.96115	2.047775	2.4503	6.6231	13.8843
Cut 22	10.29648	1.847725	2.44985	5.2223	10.9609
Cut 23	7.87718	1.6455375	2.44975	4.0367	8.4473
Cut 24	5.77536	1.4475375	2.4497	2.9572	6.212
Cut 25	3.92488	1.2473375	2.449175	2.0182	4.2134
Cut 26	2.33874	1.0450875	2.448775	1.2013	2.5346
Core (by difference with Alignment Hole)	1.40716	0.634			

Table A-18. Measured data for high-oxidation mass-loss sample (Sample 3) of graphite grade NBG-18.

NBG-18 Sample 3 after 11.33% Mass Loss, 41.2 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	94.63936	5.078	2.534		
After Oxidation	83.9185	4.975	2.534		
Faced	81.05316		2.418		
With Alignment Hole	79.67914	4.975	2.419		
Before First Cut	79.67596	4.975	2.419		
Cut 1	78.6704	4.9035625	2.419175	40.0721	84.8214
Cut 2	75.65514	4.8040375	2.418975	38.753	81.7152
Cut 3	72.46052	4.7034875	2.418525	37.2689	78.3572
Cut 4	69.3971	4.603575	2.41865	35.5452	74.922
Cut 5	66.38138	4.504975	2.41875	33.9847	71.6156
Cut 6	63.43208	4.4069	2.418875	32.4487	68.416
Cut 7	60.55036	4.3062125	2.418575	30.9893	65.3563
Cut 8	57.71307	4.206925	2.418125	29.1275	61.7992
Cut 9	54.97408	4.107925	2.41785	28.2006	59.347
Cut 10	52.31925	4.0099625	2.418225	26.7939	56.4331
Cut 11	49.67788	3.9093875	2.418425	25.4267	53.6482
Cut 12	47.09295	3.809075	2.41795	24.0155	50.7718
Cut 13	42.13215	3.6087125	2.418	21.5508	45.4203
Cut 14	37.48097	3.4088875	2.4178	19.1585	40.3386
Cut 15	33.0818	3.2115125	2.417625	16.9359	35.686
Cut 16	28.93107	3.012275	2.417775	14.844	31.1758
Cut 17	25.01528	2.811	2.417875	12.8088	26.9763
Cut 18	21.36083	2.6094875	2.4176	10.9295	22.9853
Cut 19	18.01644	2.4091625	2.417725	9.2043	19.4101
Cut 20	14.91304	2.23055	2.417525	7.6644	16.1075
Cut 21	12.09039	2.0077375	2.417425	6.158	12.9938
Cut 22	9.5512	1.8082375	2.41745	4.8017	10.2644
Cut 23	7.24989	1.606775	2.417275	3.7026	7.7999
Cut 24	5.23461	1.40615	2.417225	2.6641	5.6527
Cut 25	3.47447	1.203875	2.41685	1.7838	3.7632
Cut 26	1.99496	1.0032875	2.416275	1.0152	2.2075
Core (by difference with Alignment Hole)	1.37402	0.634			

Table A-19. Measured data for low-oxidation mass-loss sample (Sample 1) of graphite grade PCEA.

PCEA Sample 1 after 3.50% Mass Loss, 4.5 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	95.32112	5.087333333	2.55075		
After Oxidation	91.98538	5.081	2.55075		
Faced	90.01798		2.484		
With Alignment Hole	88.56488	5.081	2.484		
Before First Cut	88.564	5.081	2.484		
Cut 1	86.02248	4.993	2.484	43.9316	91.6243
Cut 2	82.68294	4.892	2.484	42.124	87.9995
Cut 3	80.63866	4.793	2.484	40.759	84.7558
Cut 4	77.5162	4.695	2.484	39.4078	81.5694
Cut 5	74.25294	4.596	2.484	37.7179	78.0273
Cut 6	70.1455	4.497	2.484	36.0259	74.6445
Cut 7	67.55782	4.397	2.484	34.5496	71.3945
Cut 8	63.88426	4.297	2.483	32.7045	67.8161
Cut 9	60.76958	4.197	2.483	31.0409	64.5889
Cut 10	58.32461	4.099	2.483	29.6513	61.6292
Cut 11	55.72891	3.999	2.483	28.4158	58.7863
Cut 12	52.67579	3.902	2.483	26.9116	55.7233
Cut 13	47.56737	3.706	2.483	24.2428	50.1812
Cut 14	43.29124	3.507	2.483	21.7403	44.9485
Cut 15	37.59334	3.307	2.483	19.1561	39.6179
Cut 16	32.77881	3.106	2.483	16.639	34.626
Cut 17	28.66176	2.905	2.483	14.5403	30.1816
Cut 18	24.85469	2.706	2.483	12.5249	26.0093
Cut 19	20.89718	2.507	2.483	10.5682	22.0494
Cut 20	17.49857	2.308	2.483	8.8399	18.4256
Cut 21	14.38736	2.109	2.483	7.3073	15.1908
Cut 22	11.51221	1.908	2.483	5.8309	12.1397
Cut 23	8.9325	1.708	2.482	4.4955	9.4191
Cut 24	6.62865	1.507	2.482	3.3657	7.0112
Cut 25	4.61968	1.306	2.482	2.3484	4.8917
Cut 26	2.89902	1.105	2.481	1.464	3.0683
Cut 27	1.4685	0.906	2.481	0.7465	1.5875
Core (by difference with Alignment Hole)	1.4531	0.634			

Table A-20. Measured data for moderate-oxidation mass-loss sample (Sample 2) of graphite grade PCEA.

PCEA Sample 2 after 8.50% Mass Loss, 9.5 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	95.30614	5.085833333	2.5455		
After Oxidation	87.20976	5.08	2.5455		
Faced	85.60662		2.482		
With Alignment Hole	84.1689	5.08	2.482		
Before First Cut	84.16792	5.08	2.482		
Cut 1	81.79476	4.989	2.483	42.5354	90.0344
Cut 2	78.95952	4.892	2.483	41.1254	86.8869
Cut 3	76.70796	4.791	2.482	39.7978	83.6055
Cut 4	74.08304	4.691	2.483	38.153	80.0773
Cut 5	70.81096	4.592	2.482	36.6169	76.6493
Cut 6	67.02012	4.492	2.482	34.906	73.3104
Cut 7	64.4762	4.39	2.482	33.5713	70.2833
Cut 8	61.55824	4.29	2.482	32.0492	66.9694
Cut 9	58.37124	4.191	2.482	30.3584	63.7404
Cut 10	55.86373	4.092	2.481	29.0901	60.8609
Cut 11	53.35727	3.992	2.482	27.8215	57.9691
Cut 12	50.48352	3.89	2.482	26.2666	54.832
Cut 13	45.48729	3.69	2.481	23.6188	49.3022
Cut 14	41.61481	3.491	2.482	21.2054	44.0903
Cut 15	36.17738	3.291	2.482	18.6839	38.9605
Cut 16	31.70725	3.09	2.481	16.1772	33.9682
Cut 17	27.65268	2.889	2.481	14.2629	29.7154
Cut 18	24.00001	2.688	2.481	12.3383	25.58
Cut 19	20.20809	2.489	2.481	10.3291	21.5457
Cut 20	16.90945	2.29	2.481	8.7046	18.087
Cut 21	13.87949	2.09	2.481	7.1021	14.8125
Cut 22	11.09595	1.89	2.481	5.5767	11.8924
Cut 23	8.58513	1.689	2.481	4.3974	9.1677
Cut 24	6.35013	1.488	2.481	3.2721	6.7904
Cut 25	4.39043	1.286	2.48	2.2237	4.6741
Cut 26	2.70649	1.084	2.48	1.3816	2.8731
Cut 27	1.32449	0.885	2.479	0.683	1.4394
Core (by difference with Alignment Hole)	1.43772	0.634			

Table A-21. Measured data for high-oxidation mass-loss sample (Sample 3) of graphite grade PCEA.

PCEA Sample 3 after 11.99% Mass Loss, 13.6 days at 500°C					
	Geometric			Archimedes	
Step	Weight (g)	Outside Diameter (cm)	Height (cm)	Suspended Mass (g)	Saturated Mass (g)
Before Oxidation	95.1969	5.086833333	2.5425		
After Oxidation	83.78462	5.073	2.5425		
Faced	81.86574		2.462		
With Alignment Hole	80.47166	5.073	2.462		
Before First Cut	80.46976	5.073	2.462		
Cut 1	78.4563	4.986	2.463	41.5291	88.3814
Cut 2	75.6065	4.888	2.463	40.0713	85.2014
Cut 3	73.13398	4.788	2.463	38.497	81.8755
Cut 4	70.64636	4.688	2.463	36.803	78.2991
Cut 5	67.54706	4.588	2.463	35.5288	75.2204
Cut 6	64.14908	4.49	2.463	33.9412	71.9561
Cut 7	61.67176	4.39	2.462	32.6127	68.9313
Cut 8	58.87275	4.289	2.462	30.9845	65.5683
Cut 9	56.0465	4.19	2.462	29.6896	62.6579
Cut 10	53.54022	4.093	2.462	28.3003	59.7482
Cut 11	51.08005	3.994	2.462	27.0463	57.0155
Cut 12	48.53581	3.895	2.462	25.5909	53.9643
Cut 13	43.70624	3.695	2.462	23.1321	48.5838
Cut 14	39.85469	3.497	2.462	20.8325	43.5808
Cut 15	34.63612	3.291	2.462	18.2577	38.2992
Cut 16	30.48246	3.091	2.462	15.9454	33.5717
Cut 17	26.61524	2.893	2.462	13.9396	29.252
Cut 18	23.05681	2.692	2.461	12.0909	25.2599
Cut 19	19.52153	2.493	2.462	10.253	21.419
Cut 20	16.33684	2.292	2.462	8.5499	17.8657
Cut 21	13.45466	2.095	2.462	7.0222	14.6725
Cut 22	10.80136	1.896	2.461	5.6119	11.7357
Cut 23	8.38519	1.696	2.461	4.3502	9.1051
Cut 24	6.2125	1.495	2.461	3.1735	6.7672
Cut 25	4.31328	1.293	2.46	2.2462	4.6899
Cut 26	2.6775	1.092	2.46	1.4081	2.931
Cut 27	1.3324	0.893	2.459	0.6816	1.4485
Core (by difference with Alignment Hole)	1.39408	0.634			