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Pebble Oxidation Behavior

ART Advanced Reactor Technologies
GAS-COOLED REACTORS

Outline

- Goal and Objectives
- Introduction and Experimental Methods
- Oxidation Results
  - Oxidation Rate
  - Uniform Oxidation?
- Conclusion and Future Work

Goal and Objectives

Mechanisms and Analysis
- Data analysis and interpretation
- Understanding the damage mechanisms is key to interpreting data

Goal

- To understand oxidation degradation of matrix graphite and its mechanism, and to support fuel vendor (Kairos Power) for fuel qualification and licensing

Objectives

- To perform oxidation testing in kinetic-controlled regime (finished)
- To provide guidance on standardization of oxidation testing of matrix graphite (ongoing)
- To study the irradiation effects on the oxidation of matrix graphite (ongoing)
- To study the oxidation effects on material properties (ongoing)

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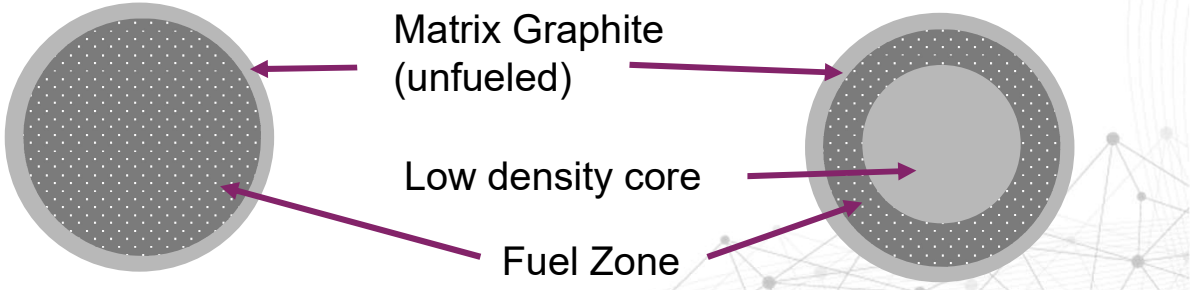
Introduction

- The fuel pebbles consist of a fuel region with fuel particles inside partially graphitized carbon matrix and a thin fuel-free carbon matrix shell to protect the fuel region from degradation and damage during handling and operation. The shell is made of a partially graphitized carbon matrix (matrix graphite).
- Oxidation concerns:
  - Acute oxidation (extremely unlikely case of air ingress)
  - Chronic oxidation
- This study is to study oxidation degradation and its mechanism of matrix graphite.



Experimental Methods

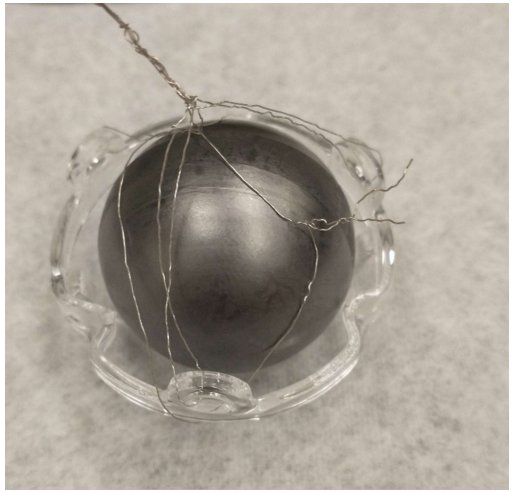
Designation: D7542 – 21

Standard Test Method for
Air Oxidation of Carbon and Graphite in the Kinetic Regime

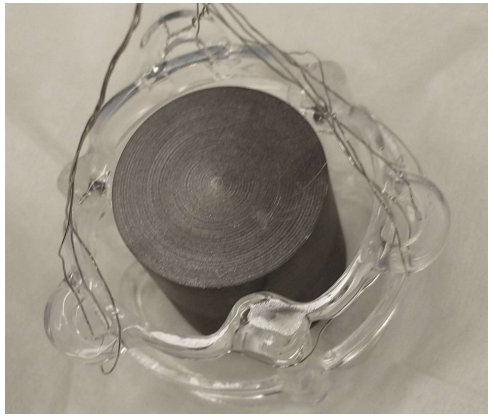
Vertical Furnace

Sample Geometries:

Vertical Furnace

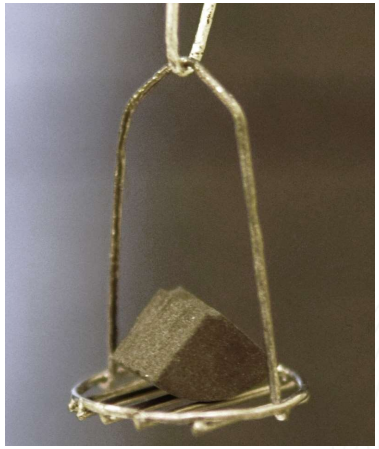


Pebble: D=40 mm
(only matrix graphite)



Standardized
cylinder
D=H=25.4 mm

TGA



Quadrant of a
disk (D~12 mm,
H~6mm)

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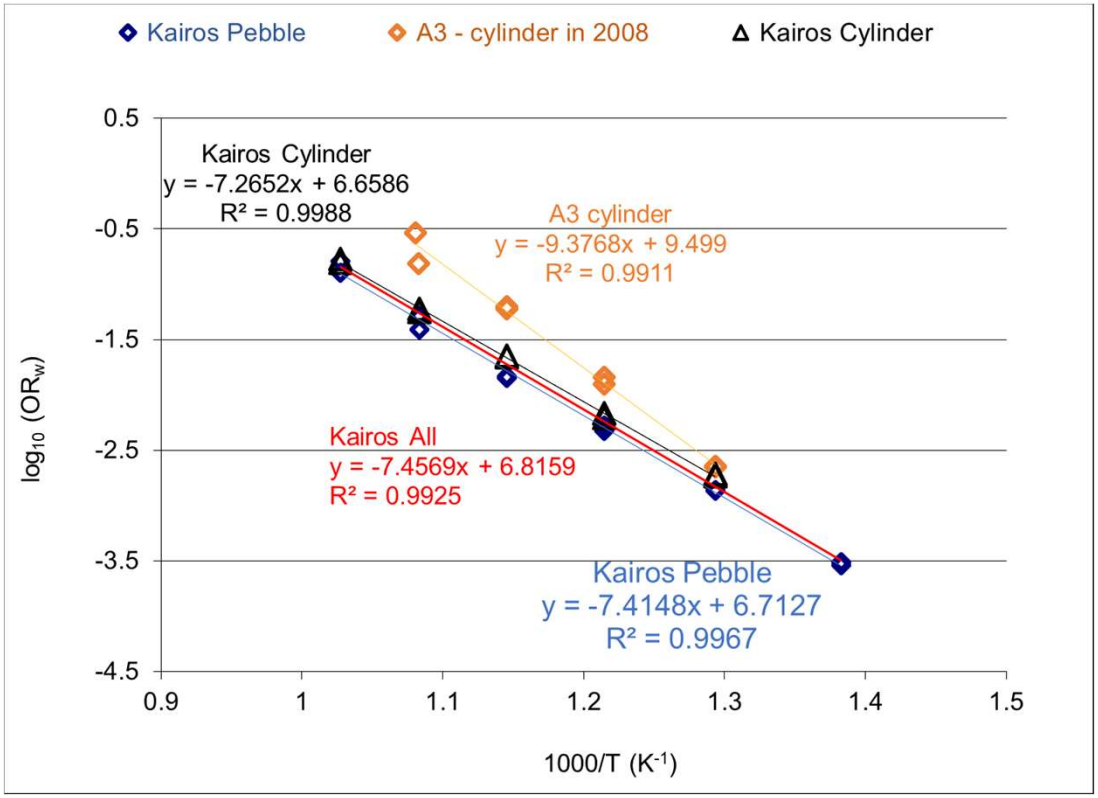
Oxidation Results – Kairos Pebble and Cylinder vs. A3

Oxidation Rate (OR_w) normalized by Weight
Temperature range: 450°C – 700°C



$$OR = A \times \exp(-E_a/RT)$$

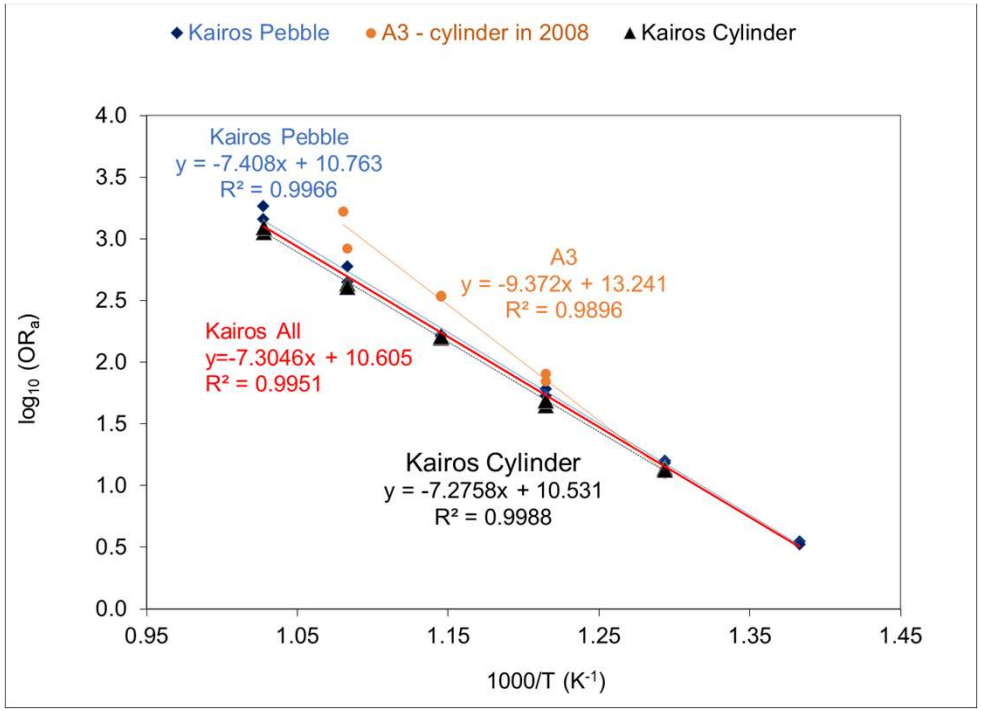
Each temperature has two samples with the same geometry.

Sample	Geometry	Ea (kJ/mol)	A ($g\ h^{-1}\ g^{-1}$)
A3	Cylinder	179.55	3.2E+9
Kairos	Cylinder	139.12	4.6E+6
Kairos	Pebble	141.95	5.2E+6
Kairos	Combined	142.79	6.5E+6

Excellent response in kinetic-controlled regime

Oxidation Results – Kairos Pebble and Cylinder vs. A3 (Cont.)

Oxidation Rate (OR_a) normalized by surface area



Sample	Geometry	Ea (kJ/mol)	A (g h^{-1} m^{-2})
A3	Cylinder	179.46	1.7E+13
Kairos	Cylinder	139.32	3.4E+10
Kairos	Pebble	141.85	5.8E+10
Kairos	Combined	139.87	4.0E+10

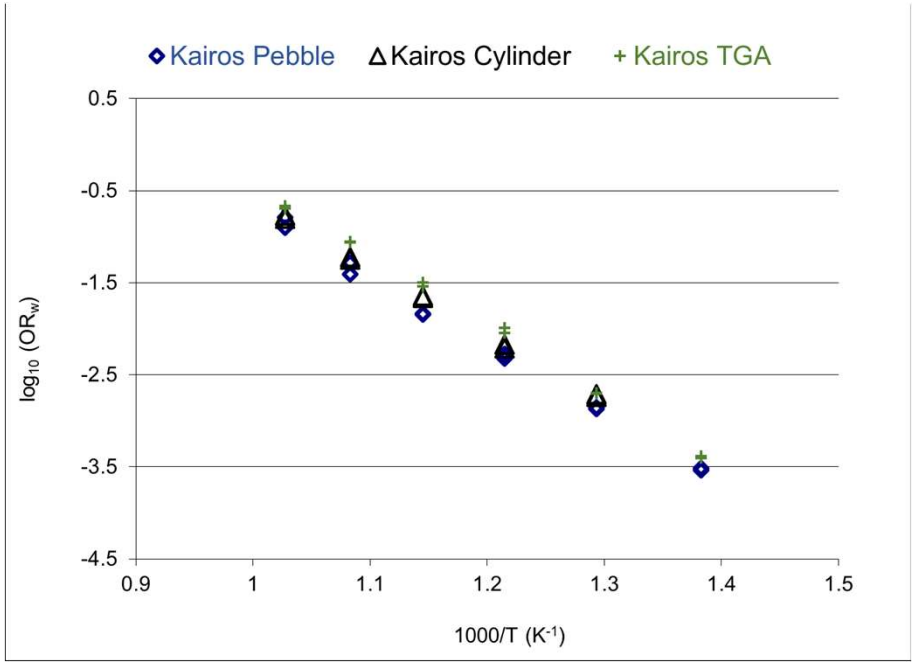
Graphite Grade	E_a (kJ/mol)	A (g h^{-1} m^{-2})
Unpurified PCEA	156	2.38E+11
IG-110	194	3.09E+13
NBG-25	211	1.89E+14
Purified PCEA	198	2.20E+13
BAN	213	1.31E+14
NBG-17	188	3.71E+12
NBG-18	190	4.17E+12

Pebble oxidized at 700°C to 10wt% loss; about 4.7% surface loose powder

The E_a and A of Kairos matrix graphite are lower than for A3 and other types of nuclear-grade graphite ➔ preferential binder oxidation?

Ref: Journal of Nuclear Materials Volume 545, March 2021, 152648

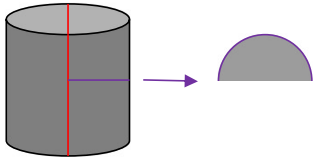
Oxidation Results –Geometrical Effects

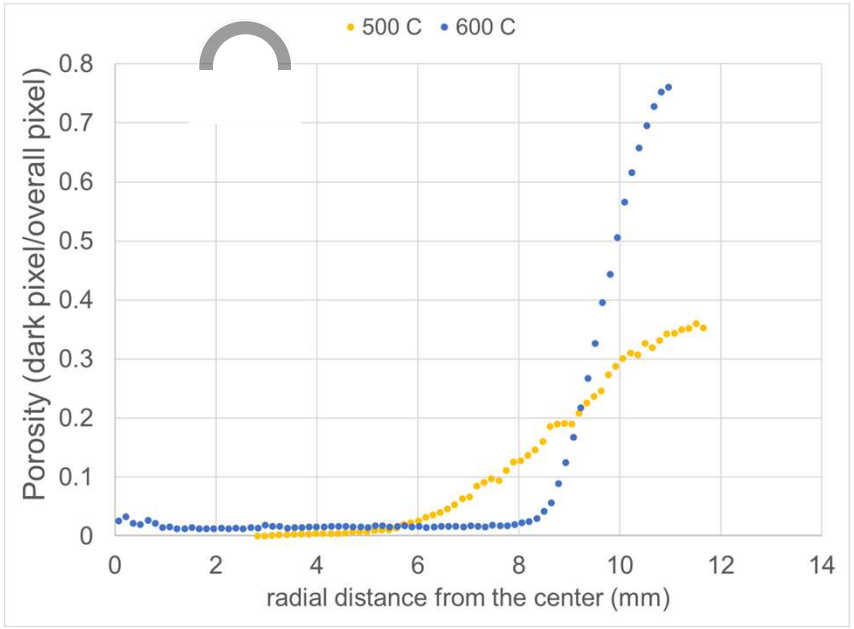


Sample	Geometry	Ea (kJ/mol)	A ($g\ h^{-1}\ g^{-1}$)
Kairos	Disk quadrant (TGA)	147.22	1.8E+7
Kairos	Cylinder	139.12	4.6E+6
Kairos	Pebble	141.95	5.2E+6
Kairos	Combined	142.74	7.4E+6

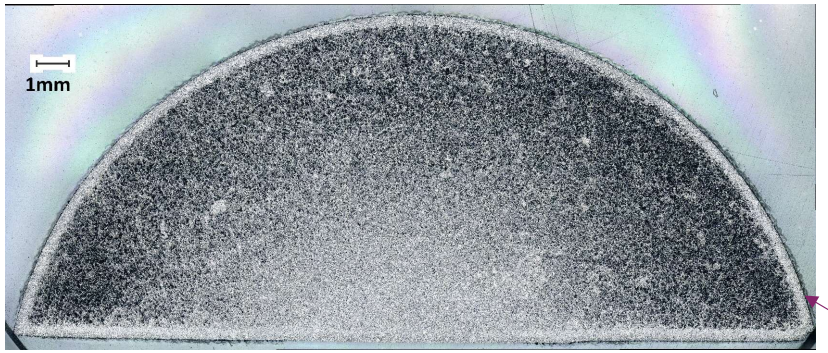
The geometrical effects (cylinder vs. pebble) are minor—merely contributing somewhat to scattering.

Uniform Oxidation?- Optical Microscope



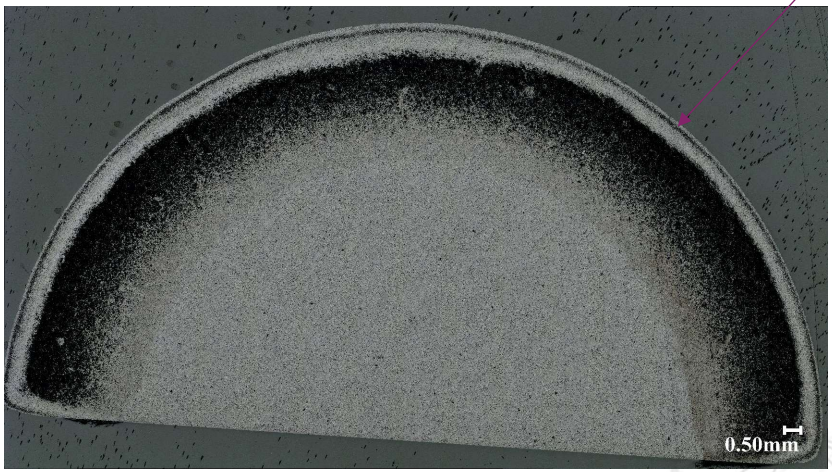


Outer severe-oxidation zone



500°C Sample #31

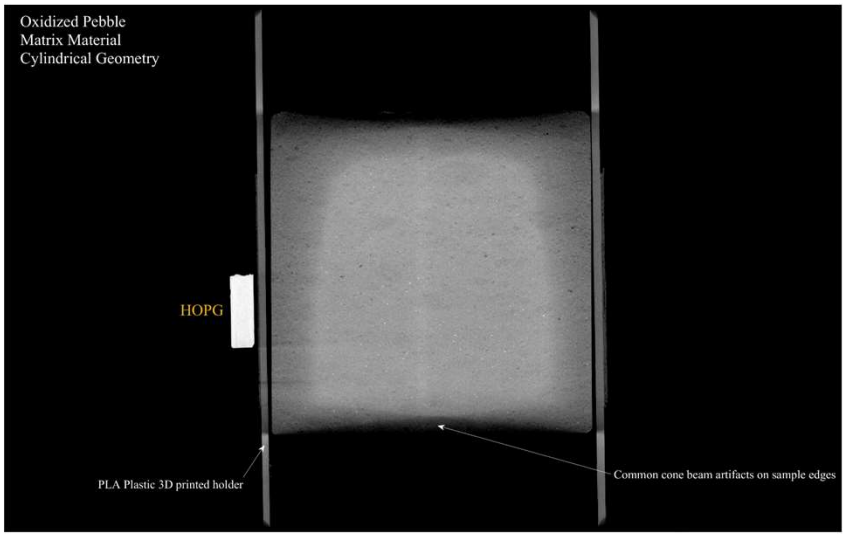
Artificial dense edge due to sample preparation

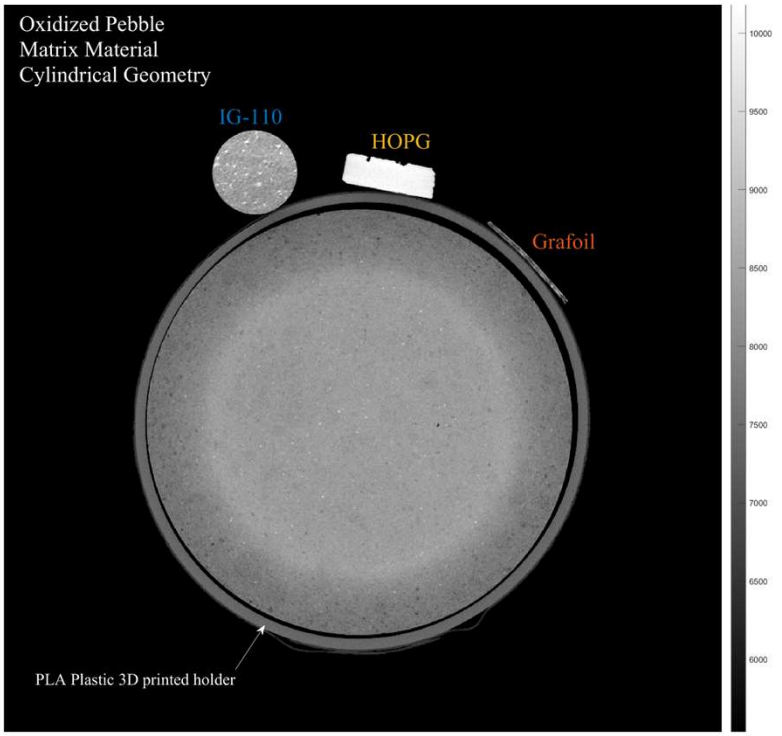


600°C Sample #20

Uniform Oxidation?- X-ray computed tomography (XCT)

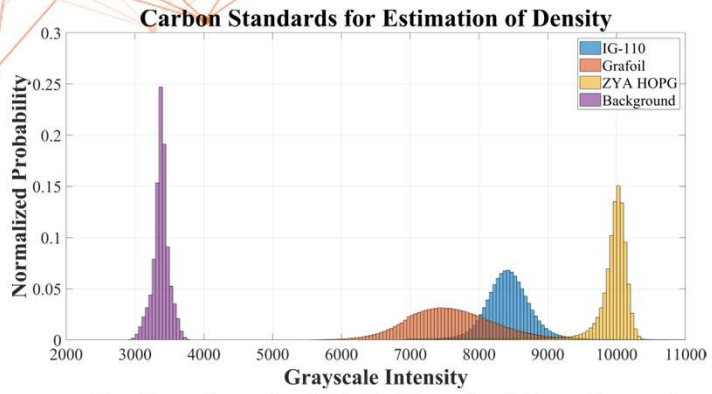
Sample # 41
Oxidized at
600°C

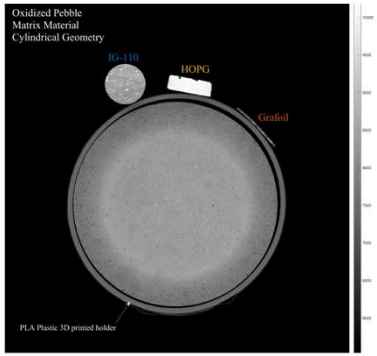


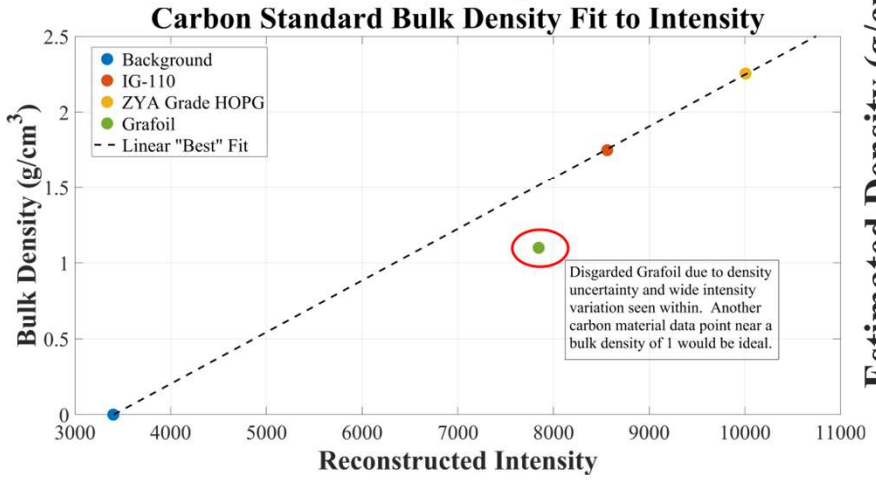


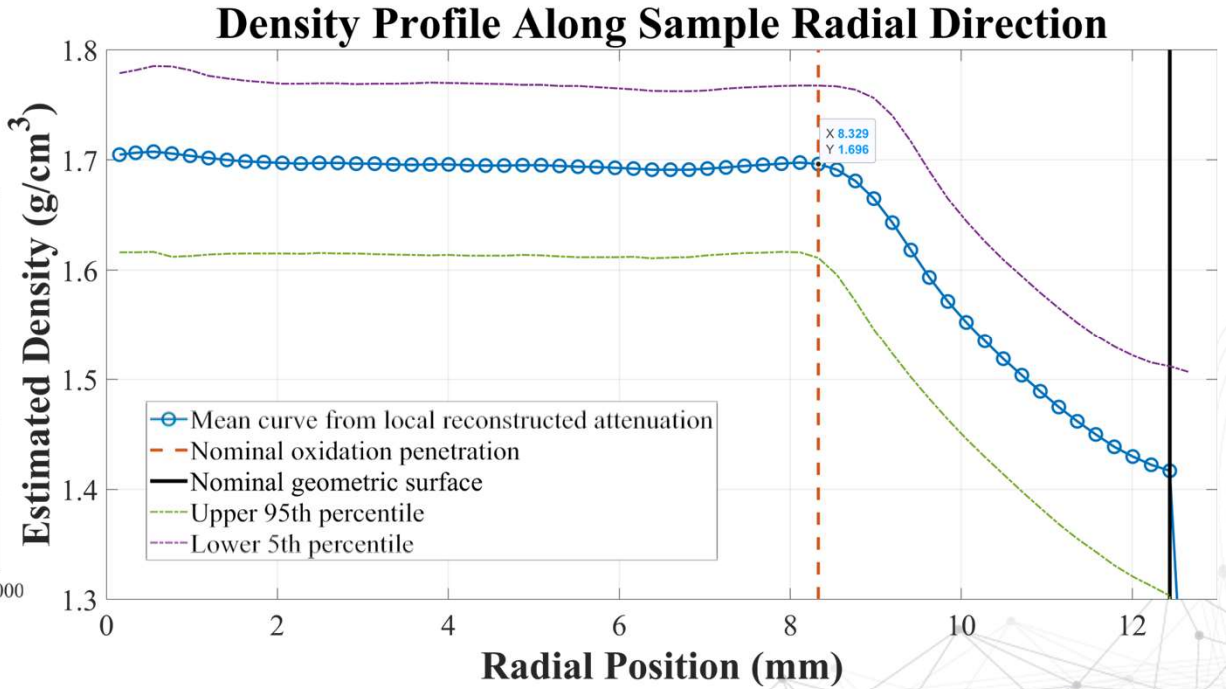
XCT confirms outer oxidation zone penetrates all exposed surfaces of the sample

Uniform Oxidation?- XCT









The penetration depth matches well with the optical microscope results.

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Conclusion and Future Work

Conclusions:

- The oxidation rate of the Kairos matrix graphite follows the Arrhenius equation at temperatures of 450–700°C. The optical microscope study shows an outer-surface oxidation zone for samples oxidized, and XCT confirms that the outer oxidation zone penetrates all exposed surfaces of the sample. The outer-oxidation zone is about 4.5 mm for the cylinder samples (D=H=25.4 mm) oxidized at 600°C from both optical images and XCT.
- Compared to the A3 matrix graphite, Kairos matrix graphite has a lower oxidation rate at high temperatures but may have a higher oxidation rate at low temperatures.
- Kairos matrix graphite has a lower E_a and A than either A3 matrix graphite or nuclear-grade graphite and may experience preferential binder oxidation.
- For oxidation in a vertical furnace, the geometrical effects—cylinder (D=H=25.4mm) vs. pebble (D~40 mm)—are small, and only somewhat contribute to scattering.

Future work will focus on how irradiation affects oxidation, and how oxidation impacts material properties of matrix graphite.