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Revision 0

Status on Development of Graphite Analytical Tool (GAT)

June 2023

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INL ART Program

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June 2023

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ABSTRACT

The U.S. Department of Energy (DOE) Advanced Reactor Technologies (ART) graphite research and development (R&D) program has been generating significant amounts of irradiated and unirradiated graphite data since 2006 when the program was part of the DOE Next Generation Nuclear Plant (NGNP) Project. This data includes critical irradiation creep and irradiated material property changes from the Advanced Graphite Creep (AGC) experiment, as well as significant amounts of data on unirradiated material property values on several current nuclear graphite grades from the baseline program. Previously, Idaho National Laboratory (INL) developed an internal analysis tool to assist with the examination of the unirradiated and irradiated data. The Graphite Analytical Tool (GAT) is intended to provide easy access to the graphite data in the form of comparing unirradiated and irradiated material property changes, a simplified comparison of material property differences between various nuclear graphite grades, and an illustration of the trends within the irradiated and unirradiated data generated within the DOE-ART Graphite R&D program. This report summarizes the progress to date on the development of this analytical tool.

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CONTENTS

ABSTRACT iii

ACRONYMS vii

1. INTRODUCTION 1
   - 1.1. Graphite Behavior 2
   - 1.2. General GAT Layout Strategy 3

2. GAT DATA 4
   - 2.1. Unirradiated (Baseline) Layout 4
   - 2.2. Irradiated (AGC) Data 7
   - 2.3. Future GAT Additions 10

3. CONCLUSIONS 10

4. REFERENCES 10

FIGURES

Figure 1. Five primary focus areas of the DOE ART Graphite R&D program. 1

Figure 2. Graphite microstructure illustrating filler particles, binder phase, and extensive porosity. 2

Figure 3. Graphite irradiation response showing material property changes as a function of received dose for multiple irradiation temperatures. 3

Figure 4. GAT introduction and menu options. 4

Figure 5. Unirradiated (e.g., baseline) data page. 5

Figure 6. Baseline reports display. 6

Figure 7. Baseline data download display. 7

Figure 8. Irradiated graphite (AGC) page. 8

Figure 9. AGC data download display. 9

Figure 10. AGC reports display. 10

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ACRONYMS

AGC	Advanced Graphite Creep
ART	Advanced Reactor Technologies
ASME	American Society of Mechanical Engineers
CTE	coefficient of thermal expansion
DOE	U.S. Department of Energy
GAT	Graphite Analytical Tool
GUI	graphical user interface
INL	Idaho National Laboratory
NGNP	Next Generation Nuclear Plant
R&D	research and development

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Status on Development of Graphite Analytical Tool (GAT)

1. INTRODUCTION

Graphite is used as a moderator, reflector, and structural component in many high temperature advanced reactor designs [1]. The U.S. Department of Energy (DOE) Advanced Reactor Technologies (ART) program anticipated the use of graphite within these new advanced reactor designs and implemented a research and development (R&D) program to investigate the behavior of the nuclear graphite grades currently available. The DOE-ART Graphite R&D program consists of five main focus areas, as indicated in Figure 1. The unirradiated, as-fabricated material properties for select nuclear graphite grades [2]are investigated within the baseline program, which is intended to provide a statistically relevant 'baseline' value for pertinent material properties. The Advanced Graphite Creep (AGC) experiment provides both irradiated material property changes and irradiation creep data, which is compared to the unirradiated baseline material property data. The other three R&D areas depend upon the analysis of the data that is generated from the unirradiated and irradiated testing programs, as well as additional information within those areas.

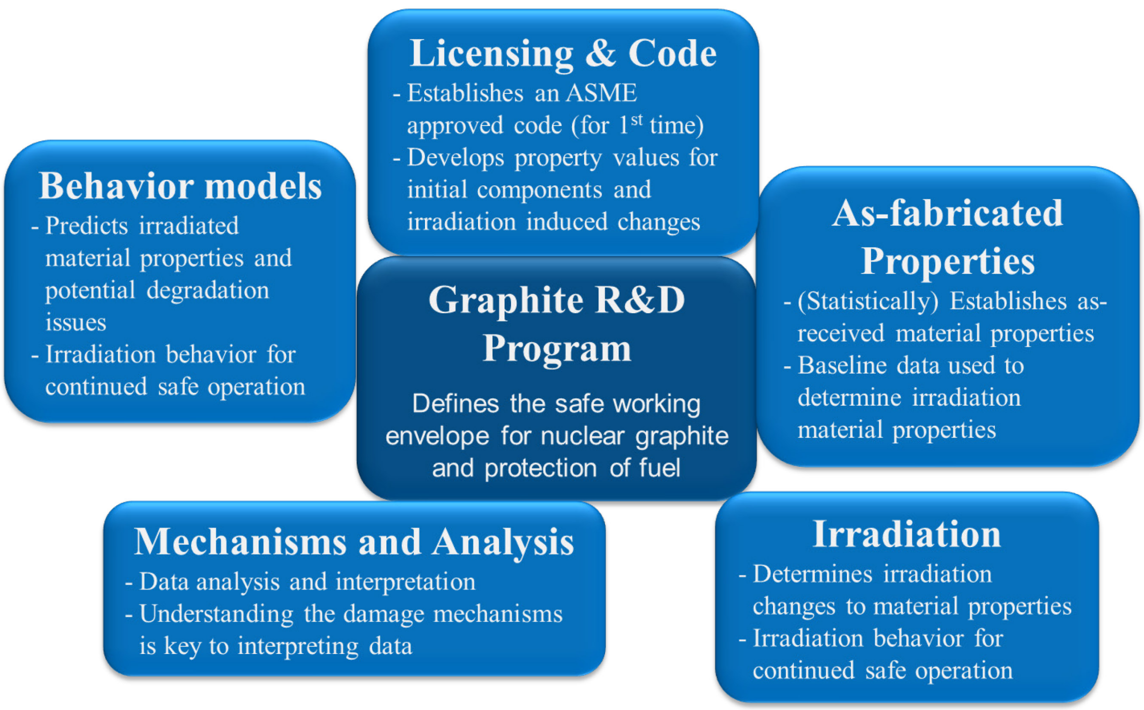


Figure 1. Five primary focus areas of the DOE ART Graphite R&D program.

To analyze and compare a large amount of material property data, the Graphite R&D program has initiated the development of an analysis tool called the Graphite Analytical Tool (GAT) to assist. To date, the GAT focuses primarily on the unirradiated and irradiated data generated within the baseline data and AGC experiment, respectively. It is anticipated that as more data analysis is performed, the GAT will incorporate additional results within the Mechanisms, Behavior Modeling, and American Society of Mechanical Engineers (ASME) Code Rule development areas of the program.

This report summarizes the initial development of the GAT and demonstrates how the tool will be used to evaluate and compare data trends for the various graphite grades investigated throughout the DOE Graphite Program.

1.1. Graphite Behavior

Graphite behaves as a quasi-brittle material with ceramic-like properties. Similar to most ceramics, graphite is stronger in compression than tension and fractures in a brittle manner. However, unlike most structural materials, graphite is intentionally fabricated with a total porosity range of approximately 15–20%, as observed in Figure 2. This porosity is essential for the expected behavior of graphite in high temperature, oxidation, irradiation, and molten salt environments.

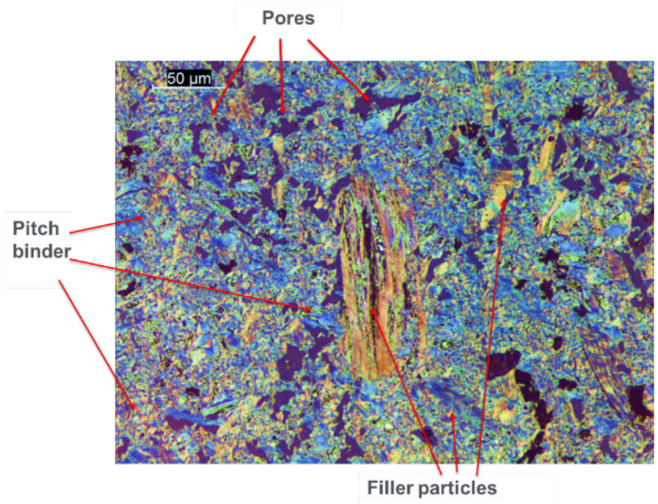


Figure 2. Graphite microstructure illustrating filler particles, binder phase, and extensive porosity.

Under irradiation, graphite components will have an unusual response in that the entire component undergoes volumetric shrinkage as a function of received neutron dose. This densification of material continues until a critical dose has been achieved where the dimensional shrinkage reverses and volumetric expansion begins, as shown in Figure 3. This key parameter is termed the turnaround dose. Strength, stiffness, and thermal expansion increases initially until a peak is achieved, and the properties then decrease with the increasing dose. It is generally understood that this behavior for these material properties is related to the dimensional change of the graphite. During volumetric decrease, the cracks and pores within the microstructure are closing due to the densification of the material, which increases the strength and stiffness of the material. This is observed to be a direct response since the turnaround dose corresponds to the peak strength and stiffness values in graphite.

It is not as clear how thermal expansion is affected by the dimensional change, but there is a correlation between the turnaround dose and the peak coefficient of thermal expansion (CTE). It is observed that graphite grades with higher turnaround dose levels also have a high CTE peak dose. The only material property that appears to be independent of the dimensional change is thermal diffusivity. Changes in thermal diffusivity occur at the atomic length scale and are not affected by changes in the overall microstructure.

These material property behaviors are illustrated with the GAT for various nuclear graphite grades. The following sections will demonstrate the analytical capabilities of the tool, which allows an easy comparison of the different graphite grades.

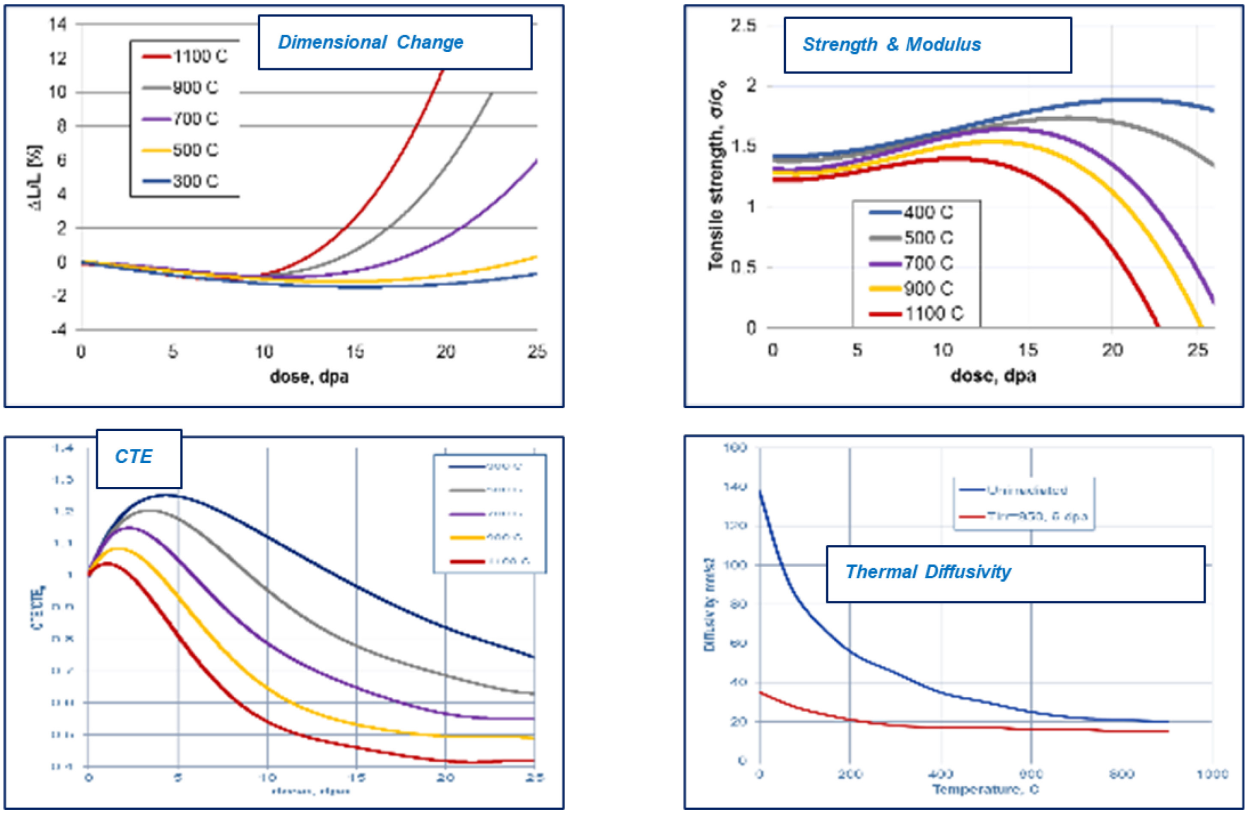


Figure 3. Graphite irradiation response showing material property changes as a function of received dose for multiple irradiation temperatures.

1.2. General GAT Layout Strategy

The GAT is composed of several different sections representative of the graphite behavior data. The data is divided into separate pages and are accessible from the 'Page Select main menu,' as indicated in Figure 4. For instance, irradiated data from the AGC Experiment is found within the 'AGC page.' Unirradiated data will be found on the 'Baseline page,' and so forth. Each page will provide drill-down options for more detailed information within the page. These additional drill-down options will be discussed in more detail in the later sections of this report.

As more data is incorporated into the GAT, additional pages will be added as needed. It is anticipated that pages providing data on Graphite Oxidation, Irradiation Damage, and possibly ASME Code Development activities will be added to the tool in the future.

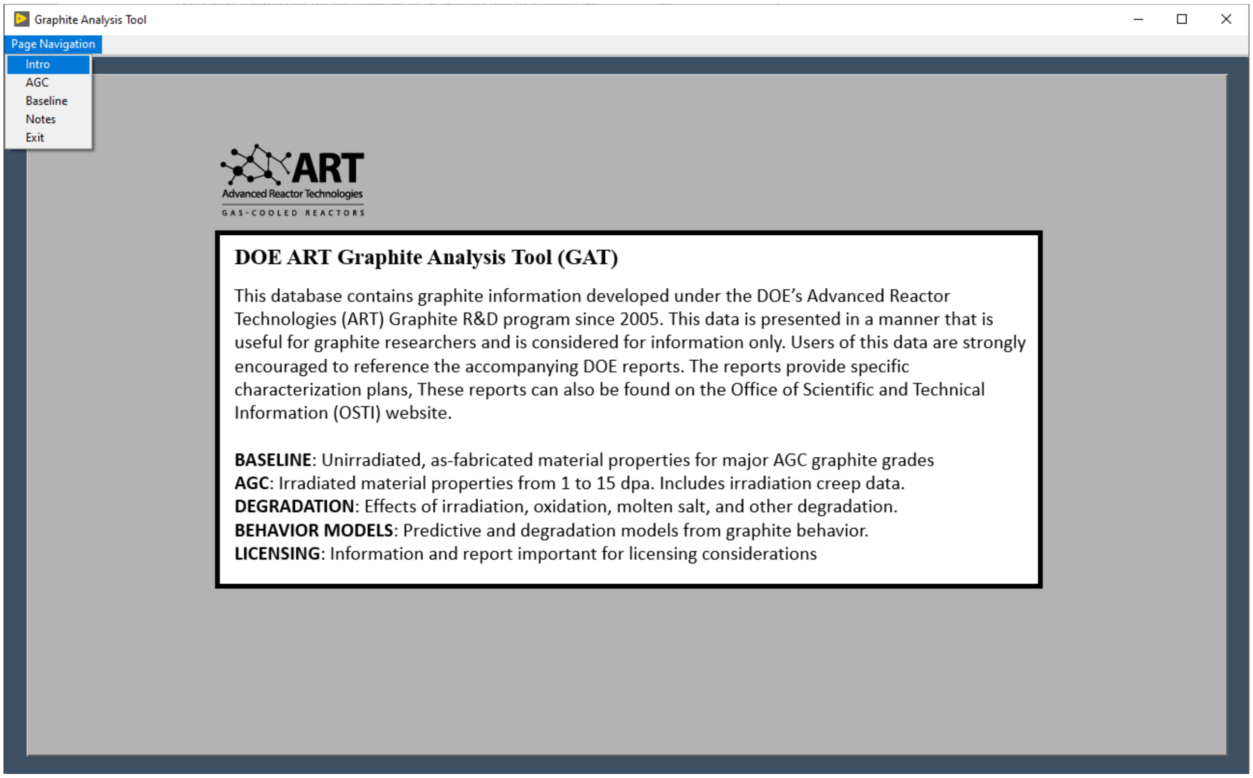


Figure 4. GAT introduction and menu options.

2. GAT DATA

The purpose of this graphite analysis tool is to help assess all data generated from the DOE-ART graphite program, including all unirradiated and irradiated data. Once the general area has been selected from the main menu, the data is organized through successive pages of information within that topic area. The following sections will detail the graphical user interface (GUI), as well as how the data is organized for the two primary areas of the unirradiated (e.g., baseline) and irradiated (e.g., AGC) data. Other data pages will be added as they become available in the future.

2.1. Unirradiated (Baseline) Layout

The unirradiated (e.g., baseline) data page provides information on as-fabricated, unirradiated material properties for a variety of graphite grades, as observed in Figure 5. The user has the option to select a single material property from a variety of different graphite grades in order to assess the measured differences between the different grades. Detailed descriptions of the page contents are provided below.

Figure 5. Unirradiated (e.g., baseline) data page.

1. Material property selection:

   - The user has the option to select several different measured material properties from the drop-down menu. The options are specimen length, specimen diameter, specimen thickness, specimen width, density, resistivity, modulus by sonic velocity method, shear modulus by sonic velocity method, modulus by sonic resonance method, shear modulus by sonic resonance method, diffusivity at 500°C, CTE at 500°C, volume, compressive stress, compressive load, compressive displacement, compressive strain, tensile strength, tensile load, tensile strain, flexural stress, flexural displacement, split disc compressive load, split disc tensile strength, split disc extension, and split disc deflection.

2. Graphite grade selection:

   - Five different graphite grades are available for comparison: NGB-17, NBG-18, PCEA, IG-110, and 2114. The user will select the grade and material property to be assessed.

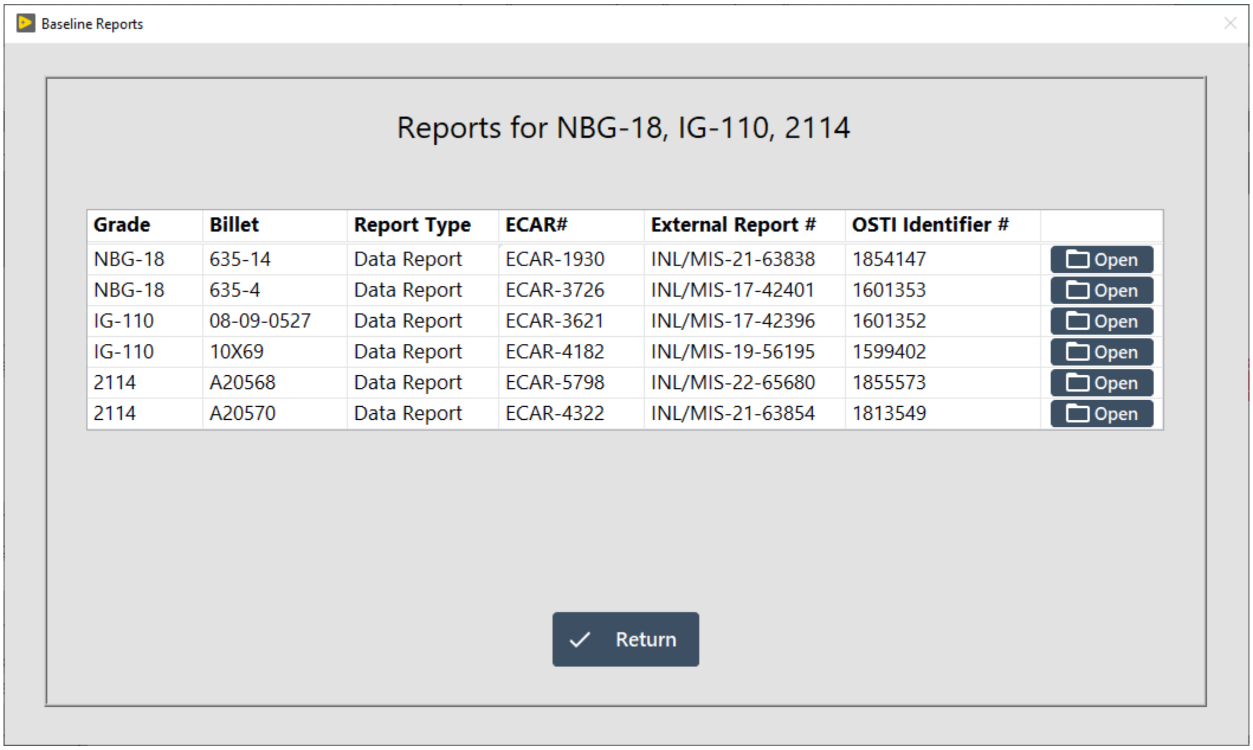
3. Data point selector:

   - The user can select specific points on the plot and the details will be displayed in the ‘Selected Data Point’ box.

4. Data statistics:

   - The descriptive data statistics are generated automatically upon selection of the grade and property. They consist of the mean, standard deviation, coefficient of variance, maximum, minimum, and range.

5. View reports:
   - The user can generate a list of pertinent reports that have been published. Figure 6 shows the baseline reports display.
6. Download data:
   - The user also has the option to download the data for the grades they have selected to a .csv file (comma-separated values). This file will allow the user to manipulate and use the data for their own specific purposes. Figure 7 shows the baseline data download display.



Grade	Billet	Report Type	ECAR#	External Report #	OSTI Identifier #	
NBG-18	635-14	Data Report	ECAR-1930	INL/MIS-21-63838	1854147	Open
NBG-18	635-4	Data Report	ECAR-3726	INL/MIS-17-42401	1601353	Open
IG-110	08-09-0527	Data Report	ECAR-3621	INL/MIS-17-42396	1601352	Open
IG-110	10X69	Data Report	ECAR-4182	INL/MIS-19-56195	1599402	Open
2114	A20568	Data Report	ECAR-5798	INL/MIS-22-65680	1855573	Open
2114	A20570	Data Report	ECAR-4322	INL/MIS-21-63854	1813549	Open

Figure 6. Baseline reports display.

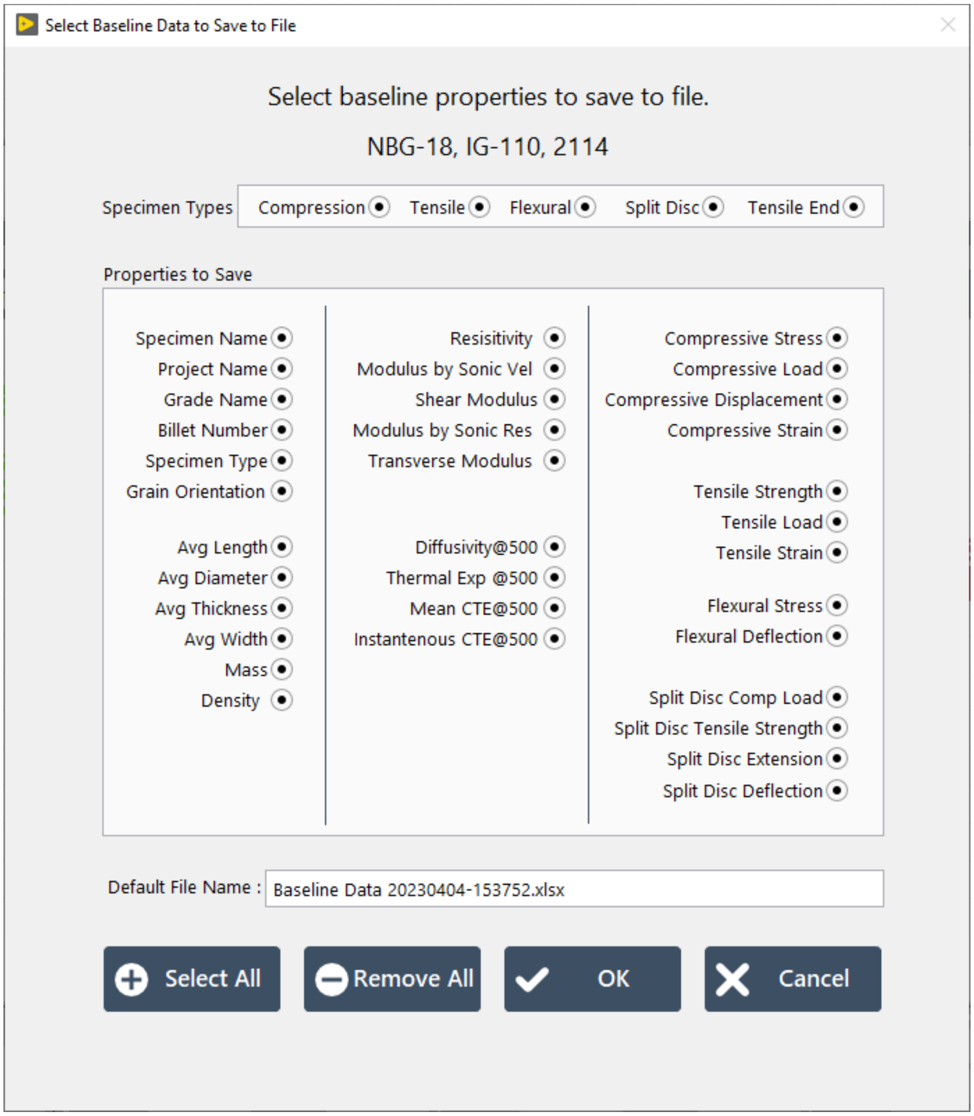


Figure 7. Baseline data download display.

2.2. Irradiated (AGC) Data

The irradiated page displays the data measurements from the AGC experiment, as observed in Figure 8. Note that the data is displayed by percentage change in material properties as a function of received irradiation or temperature, or by index against irradiated or unirradiated data.

Figure 8. Irradiated graphite (AGC) page.

1. Material property measurement:
   - The user has the option to select several different measured material properties from the drop-down menu. The options are specimen length, diameter, density, modulus by sonic resonance method, resistivity, modulus by sonic velocity method, shear modulus by sonic velocity method, CTE at 500 °C, diffusivity at 500°C, and volume.
2. Graphite grade selection:
   - Fifteen different graphite grades are available for comparison: NBG-17, NBG-18, H-451, PCEA, IG-110, IG-430, 2114, A3, BAN, HLM, NBG-10, NBG-25, PCIB, PGX, and PPEA. The user can select two different grades and material properties to be reviewed.
3. % Change data vs. the pre- or post-irradiated data:
   - The user can plot the percent change of a measurement vs. the temperature or dose. They also can plot either the pre- or post-measurements.
4. Temperature and dose range settings:
   - Sets a range for the X-axis data (e.g., temperature and dose).
5. X-axis data selection:
   - These are the X-axis options when plotting the percent change of a measurement.
6. Grain orientation selection:
   - The user can select a specific grain orientation to plot.

7. Stress levels selection:
   - The user can select specific stress levels of the specimens.
8. Save data:
   - The user also has the option to download the data for the grades they have selected to a .csv file (comma-separated values). This file will allow the user to manipulate and use the data for their own specific purposes. Figure 9 shows the AGC data download display.
9. View reports:
   - The user can generate a list of pertinent reports that have been published. Figure 10 shows the AGC reports display.

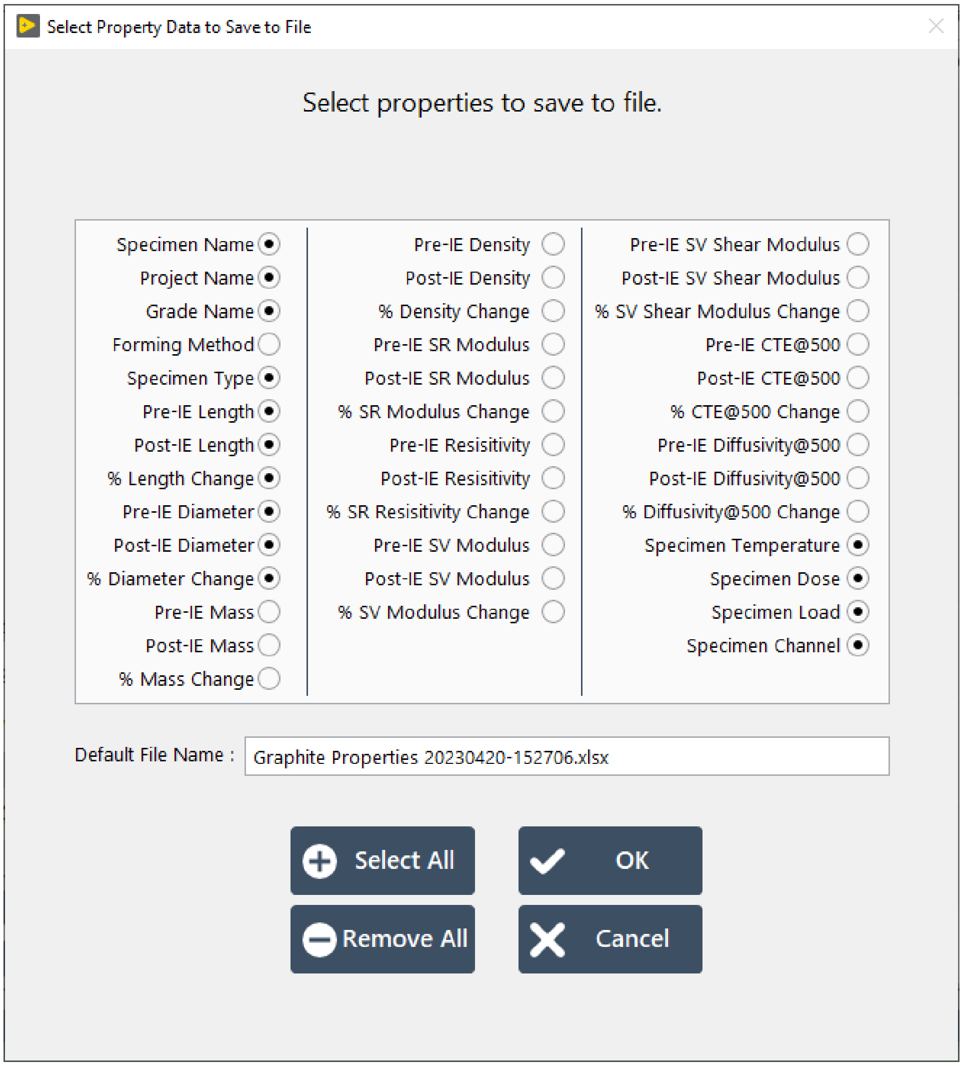
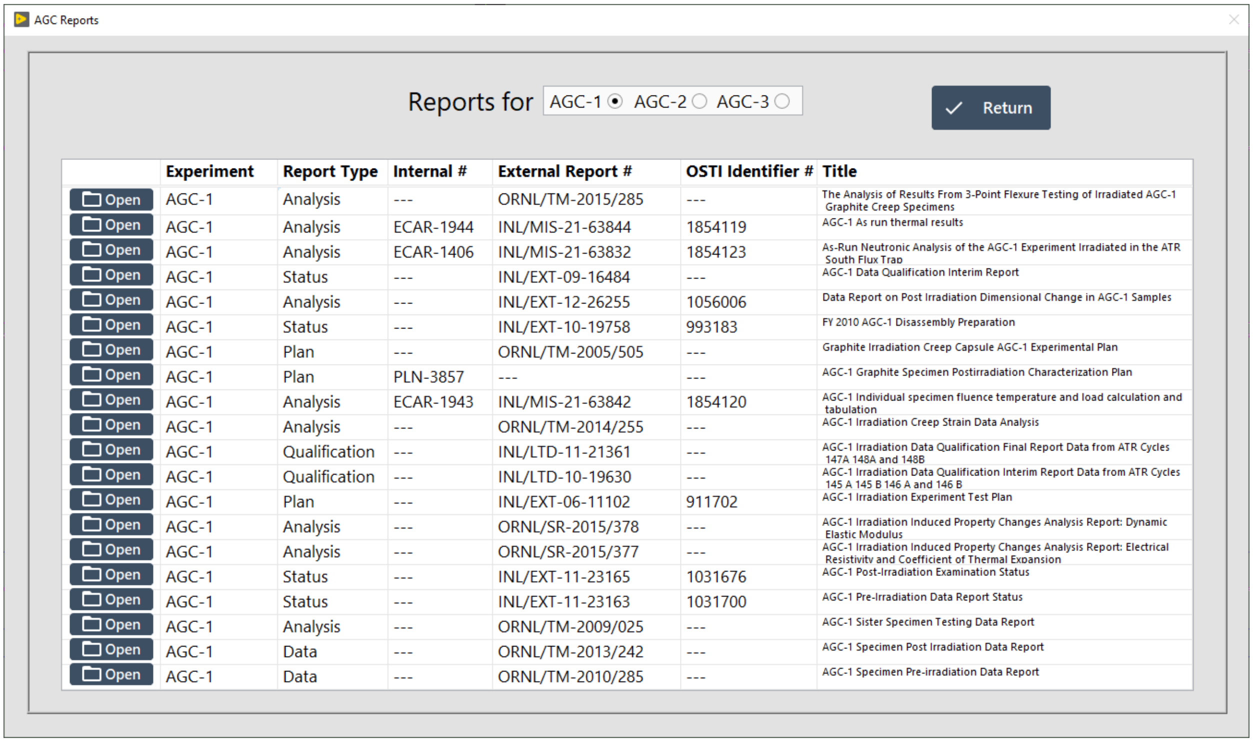


Figure 9. AGC data download display.



AGC Reports

Reports for AGC-1 AGC-2 AGC-3 Return

	Experiment	Report Type	Internal #	External Report #	OSTI Identifier #	Title
Open	AGC-1	Analysis	---	ORNL/TM-2015/285	---	The Analysis of Results From 3-Point Flexure Testing of Irradiated AGC-1 Graphite Creep Specimens
Open	AGC-1	Analysis	ECAR-1944	INL/MIS-21-63844	1854119	AGC-1 As run thermal results
Open	AGC-1	Analysis	ECAR-1406	INL/MIS-21-63832	1854123	As-Run Neutronic Analysis of the AGC-1 Experiment Irradiated in the ATR South Flux Trap
Open	AGC-1	Status	---	INL/EXT-09-16484	---	AGC-1 Data Qualification Interim Report
Open	AGC-1	Analysis	---	INL/EXT-12-26255	1056006	Data Report on Post Irradiation Dimensional Change in AGC-1 Samples
Open	AGC-1	Status	---	INL/EXT-10-19758	993183	FY 2010 AGC-1 Disassembly Preparation
Open	AGC-1	Plan	---	ORNL/TM-2005/505	---	Graphite Irradiation Creep Capsule AGC-1 Experimental Plan
Open	AGC-1	Plan	PLN-3857	---	---	AGC-1 Graphite Specimen Postirradiation Characterization Plan
Open	AGC-1	Analysis	ECAR-1943	INL/MIS-21-63842	1854120	AGC-1 Individual specimen fluence temperature and load calculation and tabulation
Open	AGC-1	Analysis	---	ORNL/TM-2014/255	---	AGC-1 Irradiation Creep Strain Data Analysis
Open	AGC-1	Qualification	---	INL/LTD-11-21361	---	AGC-1 Irradiation Data Qualification Final Report Data from ATR Cycles 147A 148A and 148B
Open	AGC-1	Qualification	---	INL/LTD-10-19630	---	AGC-1 Irradiation Data Qualification Interim Report Data from ATR Cycles 145 A 145 B 146 A and 146 B
Open	AGC-1	Plan	---	INL/EXT-06-11102	911702	AGC-1 Irradiation Experiment Test Plan
Open	AGC-1	Analysis	---	ORNL/SR-2015/378	---	AGC-1 Irradiation Induced Property Changes Analysis Report: Dynamic Elastic Modulus
Open	AGC-1	Analysis	---	ORNL/SR-2015/377	---	AGC-1 Irradiation Induced Property Changes Analysis Report: Electrical Resistivity and Coefficient of Thermal Expansion
Open	AGC-1	Status	---	INL/EXT-11-23165	1031676	AGC-1 Post-Irradiation Examination Status
Open	AGC-1	Status	---	INL/EXT-11-23163	1031700	AGC-1 Pre-Irradiation Data Report Status
Open	AGC-1	Analysis	---	ORNL/TM-2009/025	---	AGC-1 Sister Specimen Testing Data Report
Open	AGC-1	Data	---	ORNL/TM-2013/242	---	AGC-1 Specimen Post Irradiation Data Report
Open	AGC-1	Data	---	ORNL/TM-2010/285	---	AGC-1 Specimen Pre-irradiation Data Report

Figure 10. AGC reports display.

2.3. Future GAT Additions

The DOE ART Graphite R&D program has data within other areas of research, such as oxidation, irradiation damage, behavior model development, and ASME code development. These other graphite R&D program areas will be added to the system at a future date, with oxidation degradation results being the current priority. As results from the new graphite-molten salt material interactions become available, this data will be added to the GAT as well.

3. CONCLUSIONS

This report provides the initial development status of the GAT to display data generated within the DOE ART Graphite R&D program. Currently, the GAT provides data analysis for unirradiated and irradiated material properties, as well as irradiation creep response for DOE ART select graphite grades. GAT allows material property comparisons between different graphite grades and provides the percentage change in material properties as a function of received irradiation dose and irradiation temperature. This will allow DOE ART, as well as public users, to display, compare, and analyze all data generated from the DOE ART graphite R&D program.

4. REFERENCES

1. Windes, W. E., T. D. Burchell, and M. Davenport. 2020. "The Advanced Reactor Technologies (ART) Graphite R&D Program." *Nuclear Engineering Design* 362: 110586. https://doi.org/10.1016/j.nucengdes.2020.110586.

2. Burchell, T., R. Bratton, and W. Windes. 2007. "NGNP Graphite Selection and Acquisition Strategy." ORNL/TM-2007/153, Oak Ridge National Laboratory, Oak Ridge, TN. https://www.osti.gov/servlets/purl/921767.