USA DOE Advanced Reactor Technology Graphite R&D: Status 2021
**ART Graphite Program Timeline**

**Initial Development**
- Program starts 2006
- Large initial investment
- AGC-1
  - Prototype test train
  - Lessons learned from design & irradiation

**Mature Program**
- Improved/Final AGC Design
- Initial data allows:
  - Initial irr. analysis
  - Collaborations
  - Model development
  - High Dose Graphite
- Data analysis:
  - Baseline data → ASME
  - Mechanism studies data → AGC data
  - AGC data → ASME
  - Behavior Models → ASME
  - ASME Code complete

**Analysis and Implementation**
- Decision to increase AGC irradiation dose:
  - High Dose Graphite (HDG) capsules
  - Reuse VHTR capsules AGC-5 and AGC-6 (1100°C)
  - Pertinent to current commercial HTR designs

**Micro and Prismatic dose range (600°C)**

**Large PB & MSR dose range (800°C)**

**Large PB & MSR dose range (800°C)**
**Graphite R&D Program**

- Defines the safe working envelope for nuclear graphite and protection of fuel

**Behavior models**
- Predicts irradiated material properties and potential degradation issues
- Irradiation behavior for continued safe operation

**Licensing & Code**
- Establishes an ASME approved code (for 1st time)
- Develops property values for initial components and irradiation induced changes

**Virgin Properties**
- (Statistically) Establishes as-received material properties
- Baseline data used to determine irradiation material properties

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

**Irradiation (AGC)**
- Determines irradiation changes to material properties
- Irradiation behavior for continued safe operation

**Commercial**
- More interactions with commercial vendors
  - Data
  - Testing
  - Design
  - Consultation

**Five different research areas**

Commercial
## Baseline Progress

- Second and third billets of 2114 in progress.
- Second billet of NBG-17 currently being machined.
- A billet of IG-430 and a third billet of IG-110 to be initiated in FY-22.
- Over 18,000 NQA-1 qualified measurements taken so far.

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By compressively loading a disc-shaped specimen on edge the resulting tensile stresses, transverse to the loading axis, result in the specimen failing in tension transverse to the load. The load at failure, \( P \), and geometry of the specimen provide an indication of the tensile strength.
New AGC irradiation schedule better represents commercial operating envelope

- Max. dose levels now projected to 15 dpa
- 600°C & 800°C irradiation temperature
- Irradiated material properties & irradiation creep

Very high dose region:
Requires additional high dose irradiation testing for core components at these very high dose levels (past turnaround)
AGC Experiment Status:

- **AGC-1 & AGC-2**: 600°C (0.5 to 7 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-3**: 800°C (0.5 to 3.5 dpa)
  - Initial irradiation, PIE, and analysis is complete
- **AGC-4**: 800°C (3 to 8.5 dpa)
  - Irradiation complete (February 2020)
  - Disassembled July 2021
  - PIE (2021 – 2022)
  - Analysis and data to Handbook (2022)
- **HDG-1**: 600°C (7 to 15 dpa)
  - Currently out of reactor: 2 1/2 year cycle to max. 15 dpa
  - Re-irradiation of AGC-2 specimens
    - Added super-fine grain sized grades => Of interest for MSR applications
- **HDG-2**: 800°C (7 to 15 dpa)
  - Irradiation begins 2024
  - Re-irradiation of AGC-3 & -4 specimens to max. 15 dpa

### Table: Graphite Irradiation Effects

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**References**

Extraction of AGC-4 samples difficult
- Approximately 4-5 samples were clearly crushed
- A final count during PIE

High activity levels detected
- Activity levels are confusing but looks like contamination
- Initial transfer of samples to PIE facility now

PIE options based on activity levels
- AGC-4 PIE will begin next month (October)
  - Initial shipment ~ 5 samples
  - Bulk of samples shipped in October 2021
- If activity levels are too high \( \rightarrow \) PIE on the desert
  - Want to avoid this if at all possible

Extracting piggyback samples
From machined Graphite Body

Broken half of graphite body
Present & Future – High Dose Graphite capsules

HDG-1 irradiation
- Currently out of reactor during ATR CIC
- Should be re-inserted 4th quarter of 2021
- 2 of 11 irradiation cycles have occurred
  - Temperature is slightly higher than anticipated (+/- 100°C, rather than +/- 50°C)

HDG-2 irradiation
- Capsule design is unchanged
- Initial loading order has been established
  - Samples from AGC-3 and AGC-4 (800°C) will be used for HDG-2
  - AGC-4 sample activity may affect loading order
- HDG-2 will undergo irradiation immediately after HDG-1 is complete
  - Anticipated mid-2023 timeframe

Note: Finally, AGC Experiment irradiation schedule is unaffected by AGC-4 delays
Molten Salt Issues

Large molten salt tests are just being initiated at ORNL

- Salt impregnation into graphite pores
  - Physical damage/cracks
  - “Hot spots” from fueled molten salt

- Wear/abrasion/erosion
  - Molten salt has higher density than graphite
  - Liquid flow over soft graphite has potential

- Chemical coupling with metallic systems
  - Graphite – MS is inert
  - There are questions when a metallic component is added

Before immersion in FLiNaK

After immersion in FLiNaK

Salt residue

Large molten salt tests are just being initiated at ORNL
Model overview

A tool for modeling graphite is being developed at INL in MOOSE to analyze graphite components. (Multiphysics Object Oriented Simulation Environment)

The tool is intended to do the following:
1. Model degradation effects including oxidation and irradiation.
2. Determine stresses in a component based on the expected environment and loads throughout a component’s life.
3. Utilize the ASME Code to assess a graphite component (simple and full assessments).
ASME/ASTM Development

Significant progress last 2-3 years

- New testing standards
  - Graphite Classification
  - Guides (e.g. Gas Adsorption Methods)
  - Mechanical testing (e.g. Split disk tensile)
  - Physical properties (e.g. Sonic velocity)
  - Miscellaneous (e.g. Weibull)
- New Composites code rules (HBB ver. 2021)


A. Campbell “Understanding Graphite Behavior in Nuclear Reactor Environments for Lifetime Predictions”, presentation at U.S. NRC ANLWR Materials and Components Integrity Workshop, ML2003OB784, December 9-11, Rockville, MD.


D. Swank, “Status of irradiated strength studies using split disk testing”, INL Technical Report, M3AT-20IN0305040315

M. Plummer and A. Mack, “Graphite Characterization: Baseline Variability Analysis Report”, INL/EXT 18 45315, June 2018
ASTM (American Society of Testing and Materials)

ASTM committee D02.F on Manufactured Carbons and Graphite

- New ASTM Symposium:
- Graphite Testing for Nuclear Applications: The Validity and Extension of Test Methods for Material Exposed to Operating Reactor Environments
  - Excellent papers presented in a number of pertinent topic areas
  - 35+ participants
- Papers to be published in an ASTM STP (Selected Technical Publications)
- Hosted by Nassia Tzelepi (chair) and Martin Metcalfe
  - Next step – new test standards?

Symposium on Graphite Testing for Nuclear Applications: The Validity and Extension of Test Methods for Material Exposed to Operating Reactor Environments

September 23 & 24, 2021
Graphite Codes (ASME BPVC)

Progress in ASME Code development

- Latest updates on ASME graphite and composite code development
- Laundry list of new areas of optimization (Task Groups)
  - Defining failure criteria
  - Oxidation rate and effects on structural performance
  - Clarification of probability of failure (POF) assessment
  - Addition of irradiation data and trends to code rules
  - Assessment of molten salt
  - Specifications for nuclear graphite (not a standard)
Collaborations (domestic and international)

**Irradiation damage**
- Oxford
- Leeds
- Wisconsin
- Boise State
- ANSTO
- Manchester
- KAERI
- MURR

**Behavior Analysis**
- Irradiation changes
- Dimensional/creep response
- Oxidation – Exper. & modeling
- Modeling mechanical strength
- Microstructure changes/effects
- Testing and code development

**NDE**
- John Hopkins (NEUP)

**Oxidation**
- Boise State
- China (INET)
- KAERI

**Mechanical changes**
- Oxford
- Manchester
- U. Minnesota
- Boise State

**Thermal Creep**
- Manchester

**Split-disk (GIF)**
- U.K.
- China
- Australia
- Korea

**ASME, ASTM, IAEA**
- Gen IV (GIF)
- Japan
- EU
- Korea
- U.K.
- China
- NEUP
- ANSTO
- ANSTO

**Modeling**
- Manchester
- U. Wisconsin
- RPI
New portal to DOE material properties database

NDMAS (*Nuclear Data Management and Analysis System*)
- Unirradiated (Baseline) data is complete (Working out issues for access)
- Irradiated database in 2022 (hopefully)
- Link to IAEA Graphite Knowledgebase
## DOE ART Team Members

<table>
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<tr>
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<th>Expertise</th>
<th>Researcher</th>
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<td>Andrea L. Mack</td>
<td>ASME Code</td>
<td>Michael E. Davenport</td>
<td>Irradiation experiments</td>
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<td>Austin C. Matthews</td>
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<td>Nidia C. Gallego</td>
<td>Molten salt technical lead, irradiation</td>
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Update on the Gen IV Materials Handbook - Graphite Section

Presented by Nidia Gallego on Behalf of Weiju Ren

December 1, 2021
Two new members joined in the Handbook collaboration.

Gen IV Materials Handbook is a relational knowledgebase system sponsored by the U.S. Department of Energy for international collaboration in Gen IV reactor materials R&D.

• Canada rejoined in the VHTR materials collaboration and Handbook development.
  - Signatory: Atomic Energy of Canada Limited/Canada Nuclear Laboratory (AECL/CNL)
  - Canada previously withdrew from the collaboration in 2013 with its signatory Natural Resources Canada (NRCan).

• United Kingdom joined in the VHTR materials collaboration and Handbook development.
  - Signatory: Department for Business, Energy & Industrial Strategy (BEIS)

• Further information on the Handbook can be found in one of the three URLs:
  - https://michelekearneynuclearwire.blogspot.com/2019/08/knowledgebase-is-power-for-nuclear.html
In 2021, another dataset of IAEA graphite test data was collected into the Handbook for VHTR collaboration use.

- Collection approved by IAEA Technical Committee of the Nuclear Graphite Knowledge Base and supported by Dr. Windes, Dr. Reitsma, and Dr. Gallego.
- The dataset consisted of two Excel files.
  - A total of 4,165 irradiation test data from 15 graphite grades generated by 6 countries including non-PMB members Germany and Russia.
  - Conversion factors that are required for correct interpretation and use of the test data.
- Together with the first IAEA dataset, a total of 38,133 tests from 229 grades were uploaded in Chapter K-Data Package for further processing and use.
Handbook records strive to ensure foolproof interpretation and use of the data by meeting two criteria.

- **Self-Explanatory (for human)**
  - All ambiguities must be identified and clarified in the released data records.
  - The potentials of misinterpretation and misuse of the data are eliminated.
  - Posterity without the possibility to consult the data providers can unequivocally understand the information.

- **Machine-Readable (for computer)**
  - Data must be preserved and managed at the lowest meaningful information element levels.
  - The information elements can be individually and collectively operated on by computer software.