ORNL/TM-2023/2945

Summary of Vendor Irradiation Capsule Workshop Hosted at Oak Ridge National Laboratory, October 3-4, 2022

Anne A. Campbell
William E. Windes
Steven D. Johns

July 2023

OAK RIDGE National Laboratory

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ORNL/TM-2023/2945

Advanced Reactor Technology Program

SUMMARY OF VENDOR IRRADIATION CAPSULE WORKSHOP HOSTED AT OAK RIDGE NATIONAL LABORATORY, OCTOBER 3-4, 2022

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July 2023

Prepared by
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Oak Ridge, TN 37831
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ABSTRACT

The Department of Energy office of Nuclear Energy, Advanced Reactor Technology office tasked Idaho National Laboratory (INL), and Oak Ridge National Laboratory (ORNL) with hosting a set of two workshops. The primary purpose of these workshops was to convince the commercial high temperature reactor community, specifically the graphite and composite experts, to collaborate with the building and operation of a graphite/ceramic composite irradiation capsule(s). The workshops were designed to first instruct the attendees on the technical and scheduling challenges in conducting such an experiment by providing information on different technical areas in scheduling, designing, building, operating, and disassembling such irradiation capsules. A secondary purpose was to determine the individual irradiation requirements (including the desired irradiated material properties) to understand what the remaining technical needs for gas-cooled and salt-cooled advanced nuclear reactors. The first workshop was held at ORNL October 3-4, 2022. This report summarizes the discussions held during this workshop. The second workshop was hosted at INL April 4-6, 2023 and will have a separate summary report.

1. INTRODUCTION

The U.S. Department of Energy, through the office of Nuclear Energy (DOE-NE), has been responsible for the Advanced Graphite Creep (AGC) Experiment to produce irradiation effects data in graphite grades for advanced nuclear reactors. The AGC was initiated under the Next Generation Nuclear Plant (NGNP) program in 2005 and was transition to the Advanced Reactor Technology program in 2016. The AGC program consists of six irradiation capsules to be irradiated in the Advanced Test Reactor (ATR) at INL and one capsule irradiated in the High Flux Isotope Reactor (HFIR) at ORNL. The irradiation capsule at ORNL has been completed and INL is currently irradiating the fifth capsule. The sixth planned capsule is scheduled to begin irradiation in 2025. To-date the AGC program has cost ~$120M, by the time the program finishes in 2028 the total cost is expected to be $135M.

The AGC experiment was initiated under the NGNP program, which was dedicated to a gas-cooled reactor design. As a result, the six graphite grades selected for the "qualification" level study were those thought to be most desirable for gas-cooled reactors. In the ~20 years since the start of the AGC program, graphite requirements for HTR commercial applications have changed : 1) new graphite grades, different from the grades chosen for previous irradiation programs, are now being considered by HTR designers, 2) gas-cooled reactor designs have shifted from large thermal power plants (600 MW_t per module) to small-modular (100-300 MW_t) and micro-reactor (< 30 MW_t) concepts, and 3) the resurgence of interest in graphite-moderated molten salt-cooled reactors. These shifts mean that the six grades included in the AGC for ASME code qualification may not be as relevant for the newer reactor designs, or that new grades now require ASME code qualification programs. As shown with the AGC program, and with others, the irradiation programs to provide ASME code qualification data are not small undertakings [1].

The U.S. DOE-NE is not currently interested in directly funding another graphite irradiation qualification experiment such as the AGC program, and instead has expressed a desire to allow the commercial vendors assess their individual and specific requirements in this area. The desire is that these irradiations will most-likely be conducted either at ORNL or INL, and that funding for them will either be from private funding sources or through DOE-awarded funds like those from the Advanced Reactor Demonstration Program (ARDP).

However, it is understood that scheduling, designing, and operating an irradiation campaign is a complex process and the commercial HTR community will require considerable assistance. To this point, DOE tasked INL and ORNL to host a series of workshops to bring together the DOE technical experts to discuss how such an irradiation experiment can be achieved to meet the remaining irradiation requirements for graphite components in gas-cooled and salt-cooled advanced nuclear reactor applications. The first graphite Vendor Irradiation Capsule (VIC) workshop was hosted at ORNL October 3-4, 2022. This report contains a summary of the workshop attendance, agenda, and results from the open-ended discussion.

2. WORKSHOP ATTENDEES

The first graphite VIC meeting occurred over two days at ORNL, 43 persons attended/participated in the workshop with 25 participants being in-person. The list of attendees for the workshop is provided in Table 1. Affiliations of the attendees ranged from U.S. and U.K. national laboratories (ORNL, INL, NNL), graphite manufacturers (MWI/Tokai, Mersen, SGL, Toyo Tanso, Amsted Graphite Materials), reactor designers (X Energy, Kairos Power, Radiant Nuclear, Flibe Energy, Ultra Safe Nuclear Corporation, Framatome, Westinghouse Electric), university (University of Manchester), consulting (Jacobs), and regulators (US-NRC).

Table 1. List of workshop attendees and their affiliation.

NAME	AFFILIATION
Laura Bailie	ORNL
Samuel Baylis	X Energy
Zach Bednarz	MWI
Owen Booler	Jacobs
Anne Campbell	ORNL
Chong Chen	Kairos Power
Andy Covac	Mersen
Mike Davenport	INL
Mike Davies	Jacobs
Chris Fanning	Radiant Nuclear
Nidia Gallego	ORNL
Josina Geringer	ORNL
Graham Hall	University of Manchester
Kurt Harris	Flibe Energy
Steven Johns	INL
Abbie Jones	University of Manchester
Matthew Jordan	NNL Central Laboratory
Hiro Kitaguchi	Ibiden
Jason Lang	SGL
Brian LaPlant	Toyo Tanso
Victor Leight	Amsted Graphite Materials
Austin Matthews	INL

NAME	AFFILIATION
Helen Mayer	Amsted Graphite Materials
Keith Means	Westinghouse Electric
Gabriel Meric	Kairos
Takuji (Tex) Morita	Toyo Tanso
Yasuhiro Murakami	Ibiden
Gavin Noel	Amsted Graphite Materials
Jun Ohashi	Ibiden
Simon Pimblot	INL
Jarryd Potgieter	Ultra Safe Nuclear Corporation
Neil Salstrom	Ibiden
Farshid Shahrokhi	Framatome
Jacob Stager	Mersen
Kentaro Takizawa	Tokai Carbon
Alex Theodosiou	University of Manchester
Athanasia Tzelepi	NNL Central Laboratory
Adam Walker	Westinghouse Electric
Andrew Wild	Amsted Graphite Materials
William Windes	INL
Raj Iyengar	US-NRC
Alexander Chereskin	US-NRC
Christopher Ulmer	US-NRC

3. WORKSHOP SCHEDULE

The first graphite VIC workshop at ORNL spanned two days (the schedule follows in this section). The first day focused on presentation about topic related to the needs of the group. Interim Materials Science and Technology division director, Yutai Kato, started off the meeting with a welcome to the group. The presentation from W. Windes was the charge to the group. The next two talks from A. Campbell and J. Geringer were focused on code requirements and proposed changes within the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, Division 5. S. Johns next presented on on-going efforts to define bounding cases that can be used as code rules for irradiation-induced property changes, only for doses before turn-around, allowing for smaller irradiation campaigns to validate new graphite grades. Next was a presentation from M. Davenport and A. Mathews about the irradiation capabilities in the INL ATR and the Carbon laboratory for pre- and post-irradiation property measurements. K. Stiefel and A. Schrell presented an overview of the ORNL HFIR and the types of irradiations designs that have been used for graphite and other materials showing the range of capabilities available for graphite irradiation.

Emphasis was placed on the limited Material Test Reactor (MTR) options available for graphite irradiations. It was stressed that irradiation volumes are naturally limited in size due to the demands of providing high neutron flux. The irradiation positions in any MTR are not conducive for large specimen sizes (or sample populations) and a general rule of thumb is the regions in MTRs with the highest fluxes have the smallest volume available for specimens. In addition, the availability of the irradiation positions are severely limited as well. Both ATR (INL) and HFIR (ORNL) have other ongoing and future irradiation campaigns that may take a higher priority than graphite material irradiations. For ORNL, this is isotope production and neutron scattering. For INL, this is fuel qualification irradiation campaigns for all the new fuel forms being designed for both existing LWR operations as well as Advanced Reactors. Effectively, the designers will have limited irradiation volume and be in direct competition for the irradiation positions for higher priority programs. This was sobering news to many attendees.

The second day of the workshop began with tours around ORNL. The first stop was a tour of the HFIR, which was very informative to many of the attendees that had not had a previous opportunity to see the reactor. This was also informative because scale models were able to help attendees obtain a better understanding of the size of the HFIR core, flux trap, and reflector positions, which in turn helped better demonstrate the need to test small size graphite specimens due to space limitations. The next stop of the tour was the Irradiated Materials Examination Testing (IMET) hot cells located in building 3025e. The tour of the hot cells illuminated the technical challenges that arise when working with and handling highly activated materials. The final stop of the tour was the Low Activation Materials Development and Analysis (LAMDA) laboratory. The LAMDA laboratory is where all pre- and post-irradiation property measurements for graphite are performed. The LAMDA laboratory is comprised of multiple laboratory spaces, some of which are dedicated for non-activated materials, the microscopy suite which can image activated materials, and the controlled laboratory (c-zone) for activated materials. The post-tour lunch talk from W. Windes presented an overview of the DOE Advanced Reactor Technology (ART) graphite program. The afternoon time was reserved for open discussion about topics related to graphite needs to support advanced reactor development.

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AGENDA

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Commercial Graphite Irradiation Capsule Workshop

Agenda subject to change

Event contact	Host: Anne Campbell, 574-850-4171; campbellaa@ornl.gov Admin. Assistant: Laura Bailie, 865-207-5572; bailiel@ornl.gov		
Time	**Event**	**Lead**	**Place**
Monday, October 3, 2022			
7:00-8:00am	Badging Breakfast	Anne Campbell Laura Bailie	Visitor's Center 5600/H308
8:00-8:30am	ORNL Welcome	Yutai Kato	5600/H308
8:30-9:30am	Charge to the group	Will Windes Anne Campbell	5600/H308
9:30am	Coffee Break	n/a	5600/H308
10:00-10:30am	ASME code requirements and proposed changes	J. Wilna Geringer	5600/H308
10:30-11:00am	ASME irradiation code rules	Steve Johns	5600/H308
11:00-12:00pm	INL/ATR/Carbon lab overview	Mike Davenport	5600/H308
12:00-1:00pm	Working Lunch HFIR Overview and Capsule build groups	Krystin Stiefel Adrian Schrell	5600/H308
1:00-4:00pm	Discussion: Irradiation needs-dose, temperature, turn-around, creep, grades, sample size, number of samples	Anne Campbell Will Windes	5600/H308
4:00pm	Conclude		

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AGENDA

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Commercial Graphite Irradiation Capsule Workshop

Click here to join the meeting Meeting ID: 269 932 534 277 Passcode: yw4FAo

Event contact	Host: Anne Campbell, 574-850-4171; campbellaa@ornl.gov Admin. Assistant: Laura Bailie, 865-207-5572; bailiel@ornl.gov

Time	Event	Lead	Place
Tuesday, October 4, 2022			
7:30-8:00am	Arrive ORNL – Proceed to same meeting room Breakfast		5600/H308
8:00-8:45am	Open discussion	Anne Campbell Will Windes	5600/H308
8:45-11:15am	Tours Group 1 (Anne Leads) 8:45am Board bus at corner of sixth street and central avenue 9:00am HFIR Tour 9:30am board bus at HFIR – travel to 3025e 9:45am 3025e hot cell tour (Clay, Mark, & Jerid) 10:15am walk to 4508 (Southside Ave at 5th Street) 10:30am LAMDA tour (Anne & Chad) 11:00am walk to 5600-H308 (Julie)		
9:15-11:45am	Tours Group 2 (Laura leads) 9:15am Board bus at corner of sixth street and central avenue 9:30am HFIR Tour 10:00am board bus at HFIR – travel to 3025e 10:15am 3025e hot cell tour (Clay, Mark, & Jerid) 10:45am walk to 4508 (Southside Ave at 5th Street) 11:00am LAMDA tour (Anne & Chad) 11:30am walk to 5600-H308 (Anne)		
11:15-12:00pm	Open discussion	Anne Campbell Will Windes	5600/H308
12:00-1:00pm	Working Lunch ART Graphite Program Overview	Will Windes	5600/H308
1:00-2:00pm	Discussion: Vendor specific needs (temperature, doses, specimen sizes)	Anne Campbell Will Windes	5600/H308
2:00-4:00pm	Discussion: Designs and modifications to meet majority of needs of the group	Anne Campbell Will Windes	5600/H308

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AGENDA

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Event contact	Host: Anne Campbell, 574-850-4171; campbellaa@ornl.gov Admin. Assistant: Laura Bailie, 865-207-5572; bailiel@ornl.gov

Time	**Event**	**Lead**	**Place**
Tuesday, October 4, 2022			
4:00pm	Follow up meeting plan	Will Windes	INL Spring 2023
4:15pm	Conclude		

Tour Group #1	***Tour Group #2***
Anne Campbell	*Laura Bailie*
Julie Adams	*Matthew Jordan*
Samuel Baylis	*Andrew Wild*
Jason Lang	*Victor Leight*
Andy Covac	*Gavin Noel*
Takuji Tex Morita	*Chris Fanning*
William Windes	*Kurt Harris*
Steven Johns	*Jacob Stager*
Mike Davenport	*Keith Means*
Neil Salstrom	*Adam Walker*
Yasuhiro Murakami	*Brian LaPlant*
Hiro Kitaguchi	*Nidia Gallego*
Josina Geringer	J. David Arregui-Mena

4. DISCUSSION SUMMARY

The planned discussion for Monday afternoon was reduced to less than one hour due to the talks and associated discussions taking longer than scheduled. Most of the first day's discussion was focused on questions asked by the audience that require further investigation. These included:

- What are requirements for demonstration reactors on DOE sites (not NRC approvals)?
- Will the generalization/data bands S. Johns is working on for dimensional change also be expanded to other properties?
- What are the challenges facing reactor designers?
- M. Davies (Jacobs): We may need to publish a handbook of graphite data that is analyzed, reported by the graphite experts, and peer reviewed. 'Currently, the data is scattered around the world; how can we generate the curves for the different temperatures for interpolation to support the effort being led by Steve?'

Tuesday afternoon had a much more in-depth discussion about various needs and concerns from both reactor designers and graphite manufacturers. One of the more interesting discussions focused on the non-proliferation treaty (NPT) as it greatly affects the ability to ship high purity graphite. The primary concern is that for any high-purity graphite shipments of more than 0.5 kg an export control license is required by the country that produced the material. Input from T. Morita (Toyo Tanso) indicated that such an export license and end-user certificate can take upwards of a year to obtain the necessary approvals. N. Salstrom (Ibiden) suggested that some of the issues come down to end use rather than a grade is considered a "nuclear graphite". The other concern, outside of the bounds of the NPT, is for fine-grained grades that also fall under other export requirements related to rocket nozzles. W.Windes indicated that these issues have been raised with the DOE ART national technical director to have them begin to raise this set of concerns with the US DOE.

The next topic focused on the needs of the different reactor designers/vendors for additional irradiation programs. A summary of the needs provided by the vendors for both irradiation needs, questions, and graphite procurement (when discussed) are given here. As a note for scale, a single billet of PCEA produced by Amsted Graphite Materials is 18 inches in diameter and 72 inches long and weights roughly 1 ton.

- Westinghouse eVinci: higher temperatures (700°C – 1000°C) and doses approaching or slightly past turn-around
- Flibe Energy: 700°C, doses at or near turn-around, considering going to crossover
  - Are there ways to seal the surface of graphite to prevent salt permeation?
  - How can we bond graphite pieces to form longer channels?
  - Can we braze metals to the ends of graphite pieces (ideal originally posed for ORNL molten salt breeder reactor)?
- Ultra Safe Nuclear Corporation: 300°C – 800°C below 5 dpa for demonstration plant, but commercial team is considering increasing final dose
  - How easy will it be to design a new irradiation capsule if we only need a few data points?
  - Expect to order/procure multiple hundreds of tons in the next 5-7 years
- Radiant: 500°C – 800°C graphite before turn-around
  - As new batches of graphite are produced does it fall to companies to qualify a new batch? Is this the same grade as what was previously produced?

- X Energy: Xe-100 <300°C – 750°C, high dose good, not extreme temperature, creep at 400°C and high dose
  - Build 4 Xe-100 cores by 2030 multiple hundreds of tons needed
- Kairos: ETU-10 graphite, irradiation creep, 500°C – 700°C, past turn-around
  - Estimate 10s of ton per core

The next discussion was more focused on needs related to requirements in the ASME Boiler and Pressure Vessel Code, Section III, Division 5 [2].

- Does an irradiation campaign require the use of multiple billets from different batches or if one would be sufficient?
  - The short answer is no, because once the billet-to-billet variability is quantified via Article HHA-III-4000 in the ASME code [2] then using a single billet shouldn't be an issue.
- What is the <u>minimum</u> number of specimens that need to be tested to quantify the billet-to-billet variability?
  - The answer for unirradiated qualification is 144, which comes from the requirements in HHA-III-4000 to sample **3 charges** (lots), at least **4 billets per charge**, billets will be sectioned into **3 axial slices**, and specimens with orientation to the **2 distinct orientations** (with- and against-grain) will be taken from **2 radial positions** of each slice (center and periphery) ($3\times4\times3\times2\times2=144$).
- C. Chen (Kairos): Coke suppliers can change the raw material (mixing multiple source materials) to meet desired specifications, should the specifications for grades be based on the raw materials specifications rather than the supplier?
  - J. Lang (SGL) and N. Salstrom (Ibiden) both confirmed that the specifications for the cokes have consistent requirements rather than being tied to a specific coke supplier.
  - V. Leight (AGM) should the definition of a grade depend on the materials properties and processing route rather than source materials?
- G. Meric (Kairos): Can we get away with not doing creep experiments and instead use trends to develop bounding curves?
  - W. Windes stated that in his opinion, such bounding curves may be defensible up to turn-around, but anything past would require experimental results.

Discussion also touched on the current state of graphite supply and demand and how that could affect availability for building advanced reactors. N. Salstrom (Ibiden) pointed out that the nuclear industry will be competing with semiconductor, solar, and other industries for the next 5-10 years and that those competing industries don't have the additional constraints of needed export licenses under the Non-Proliferation Treaty, which can make supplying to nuclear reactor needs less desirable. The recent US government CHIPS bill signed in 2022 is already having an impact on graphite demand as well, due to the rapid increase in semiconductor production plants. N. Salstrom (Ibiden) indicated that with the current graphite demands, that if a reactor vendor was to start discussions today for procurement of ~100 tons, it would be roughly 7 years before material delivery. The question was posed :"what time and cost investment would be needed to startup additional production capacity?" to which the reply was "there has not been an order placed for graphite for a nuclear reactor core since discussions first started in the early 2000s, so why should manufacturers increase production capacity without any guarantee on the return on investment." It was also noted that various graphite vendors have paid for preliminary irradiation campaigns to provide starting information about their materials response to neutron irradiation, which has not yet provided any return on investment in the form of a US-based order to support the construction of a reactor core. The key takeaway from this last discussion is: **Graphite supply may be a short-term critical supply chain issue in the deployment of advanced nuclear reactors until new production capabilities are added.**

5. FINAL THOUGHTS

This first graphite VIC meeting was a mixed success. No reactor vendor agreed to collaborate with another on the design and cost sharing of a common irradiation capsule. The prospect of losing intellectual property advantage to their competitors is keeping the new HTR vendors from agreeing to sharing the experimental costs as well as sharing the data. However, the vendors now have a more accurate perspective on the difficulties (and long time spans) needed for an irradiation campaign. The fact that the volumes and irradiation positions within the MTRs at ORNL, INL, and even HTR (Petten) are severely limited for the next decade also was sobering for many commercial vendors. This more realistic understanding of the true costs for such endeavors may counteract their reticence in collaborating on this expensive qualification step.

The supply chain issue is a difficult problem to define. While it is recognized that the current supply of high-purity grade graphite necessary for nuclear as well as semi-conductor technology is severely restricted, this is a temporary problem that can be solved by the graphite suppliers increasing production. While, there does not appear to be a near term shortage of raw material supply, the issue appears to be one of production capability for high purity, highly isotropic graphite grades. The fact that the suppliers don't want to incur the cost of expanding their production unless there is a clear demand for their product will eventually be solved once the new HTRs begin construction. However, it is recognized in the short term that this may be a challenge and additional cost to the HTR industry. The additional restrictions placed by the NPT on graphite for nuclear applications as well as fine-grain grades for defense purposes will result in an added cost and time to meet these regulations.

6. REFERENCES

[1] Campbell, A.A., "Perspective on "code qualifying" new graphite grades for use in advanced nuclear reactors*", *Frontiers in Nuclear Engineering*, **1**, (2022) 1045607.

[2] "ASME Boiler and Pressure Vessel Code An International Code, SECTION III Rules for Construction of Nuclear Facility Components, Division 5 High Temperature Reactors", ASME, New York, NY,