INL/RPT-23-74712
Revision 0

Options, Initial Design Requirements, Estimated Costs, Reactor Commitments, and Potential Uses of a Graphite Leadout Type Experiment Supporting Various Commercial HTR Vendors

September 2023

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INL ART Program

Options, Initial Design Requirements, Estimated Costs, Reactor Commitments, and Potential Uses of a Graphite Experiment Supporting Various Commercial HTR Vendors

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ABSTRACT

Multiple commercial High Temperature Reactor (HTR) vendors and nuclear graphite suppliers would benefit by collaborating on a new irradiation capsule(s) that would include graphite grades not included within the Advanced Graphite Creep (AGC) experiment. This new irradiation capsule(s) would provide data to answer vendor graphite licensing issues. Rather than investing money and time in designing separate irradiation capsules for each designer, the capsule(s) would be used for multiple graphite and composite designs to maximize efficiency and promote multiple HTR designs. However, the primary motivation for assisting vendors with this new irradiation capsule(s) is its lack of availability in the existing Material Test Reactors (MTRs). Cost reduction is a secondary goal. A common, collaborative capsule design can be achieved for graphite and composites due to the similarity of different grades. Irradiation, disassembly, shipping, and post-irradiation examination (PIE) costs would be cost-shared by all users. Interest is anticipated to extend across all DOE campaigns (e.g., micro-Rx, SMR, GCR, MSR) due to the similar requirements for all graphite grades.

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ACRONYMS

AGC	Advanced Graphite Creep
AGR	Advanced Gas Reactor (Fuel irradiations)
ATR	Advanced Test Reactor
HFIR	High Flux Isotope Reactor
HFR	High Flux Reactor
HTR	High Temperature Reactor
INL	Idaho National Laboratory
MeV	Mega electron Volts
MIF	Materials Irradiation Facility
MTR	Material Test Reactor
MWt	Megawatt thermal
NGNP	Next Generation Nuclear Plant
ORNL	Oak Ridge National Laboratory
RB	Removable Beryllium
VIC	Vendor Irradiation Capsule
VXF	Vertical Experiment Facility

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1. INTRODUCTION

The U.S. Department of Energy, through the office of Nuclear Energy (DOE-NE), has sponsored 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 transitioned to the Advanced Reactor Technologies program in 2016. The AGC program consists of six irradiation capsules that will be irradiated in the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) and one capsule that will be irradiated in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The irradiation capsule at ORNL has been completed used for high temperature graphite irradiations. INL is currently irradiating the fifth capsule and is planning to begin irradiation of the sixth capsule in 2025 (see Figure 1).

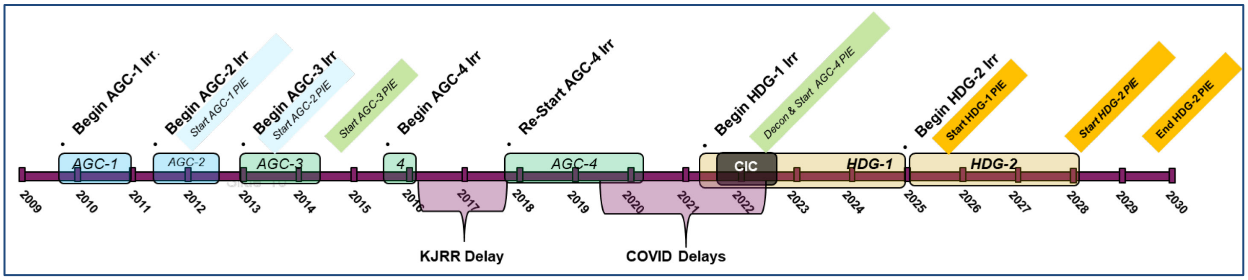

Figure 1. AGC past and anticipated irradiation schedule.

The AGC experiment was initiated under the NGNP program, which was dedicated to a gas-cooled reactor design. As a result, the six major graphite grades selected for the AGC "qualification" level study were those thought to be most desirable for gas-cooled reactors in the early 2000s. In the approximately 20 years since the AGC program began, graphite requirements for High Temperature Reactor (HTR) commercial applications have changed:

1. New graphite grades are now being considered by current HTR designers. This includes gas-cooled, molten salt-cooled, and microreactor designs.
2. HTR designs have shifted from large thermal power plants (600+ MW_t per module) to small modular reactor (100-300 MW_t) and microreactor (< 30 MW_t) concepts.
3. New designs that have lower or higher operating temperatures than the AGC are currently being investigated.
4. There is a new interest in graphite-moderated molten salt-cooled reactors.

These shifts mean that the six grades included in the AGC for the American Society for Mechanical Engineers (ASME) code qualification may not be relevant for the newer reactor designs and that new grades will require ASME code qualification programs. It is not a small undertaking to provide ASME code qualification for the irradiation programs, as shown with the AGC program and other programs.

Currently, the U.S. DOE-NE is not considering funding another graphite irradiation qualification experiment. Instead, DOE-NE is encouraging commercial vendors to independently pursue their individual and design-specific requirements for any new graphite irradiation experiments. It is assumed that these irradiations will be conducted within the Material Test Reactors (MTRs) at ORNL and/or INL and that funding will come from private funding sources or through DOE-awarded funds like the Advanced Reactor Demonstration Program.

2. PROBLEM STATEMENT

There are several graphite vendors (e.g., MWI/Tokai, Mersen, SGL, Toyo Tanso, and Amsted Graphite materials) and reactor designers (e.g., X-Energy, Kairos Power, Radiant Nuclear, Flibe Energy, Terrestrial Power, Moltex, Ultra Safe Nuclear Corporation, Framatome, Westinghouse, and BWXT) that may require additional data on irradiation-induced property changes for their respective graphite grades to support ASME code rule modification and, ultimately, licensing by the Nuclear Regulatory Commission (NRC). However, because U.S. DOE will not directly fund a new graphite irradiation campaign, there is not enough space to support this effort within the available MTRs worldwide. Figure 2 illustrates the limited space available in the three most powerful MTRs in the world. While there appears to be a many irradiation positions available in all three MTRs, the reality is that positions are already filled with other advanced reactor material experiments. ORNL's HFIR only has between one and two target positions available, INL's ATR has a similar number available, and HFR (Petten) realistically only has one position available.

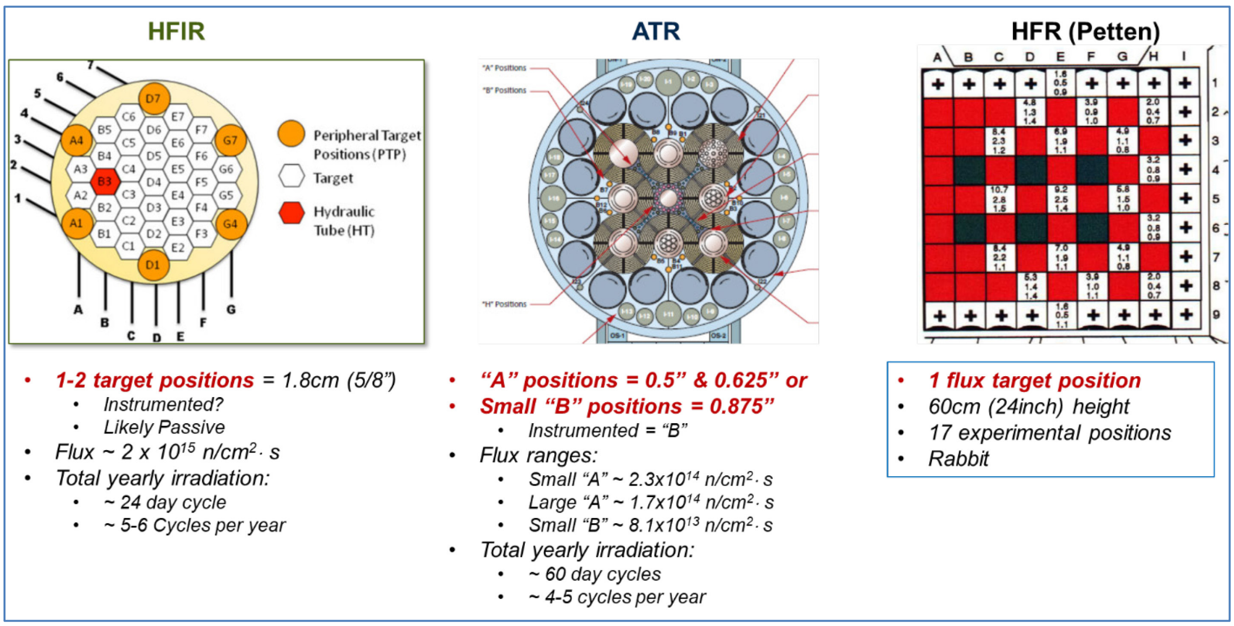

Figure 2. Three primary MTRs available worldwide showing the limited number of irradiation positions available.

Additionally, the large microstructure features of nuclear graphite require relatively large test specimen sizes. The key material properties for predicting core component behavior include strength, elastic modulus, coefficient of thermal expansion, thermal diffusivity, irradiation-induced dimensional change, and critical irradiation-induced creep rate. Accurate measurements of dimensional change, strength change, and creep rate require rather large specimen (AGC specimen = 12.5mm diameter by 25mm long). This factor creates additional problems in that graphite irradiation experiments are large volume experiments compared to metallic or fuel capsule experiments.

Finally, the critical turnaround dose, which directly impacts dimensional change and internal stress states within core components, also signals when other properties will significantly deteriorate. The turnaround dose is highly dependent upon the coke source and manufacturing process, so each nuclear graphite will have a unique response under irradiation. Irradiation temperature is an addition factor affecting the turnaround dose requiring multiple experiments conducted at different temperatures. This demonstrates that qualifying each grade of nuclear graphite individually at various temperature regimes is time consuming and expensive, making the individual graphite qualification approach unreasonable. A realistic schedule illustrating the time required to irradiate graphite samples is shown in Figure 3.

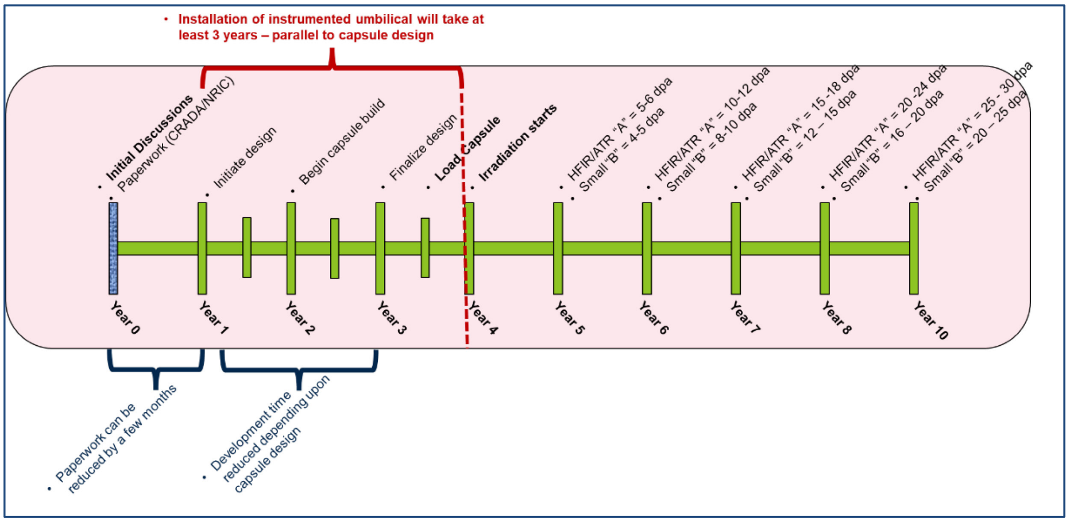

Figure 3. A realistic timeline to design, build, and irradiate an experimental capsule filled with graphite specimen.

The most cost effective and expeditious approach to resolving these key issues are as follows:

1. Continue obtaining AGC graphite irradiation data as DOE scales back its funding
2. Devise a streamlined process to obtain the required irradiation properties for multiple graphite grades to meet ASME code rule requirements and acceptance by NRC.

3. VENDOR IRRADIATION CAPSULE (VIC) CONCEPTS

One possible solution to the issues raised starts with an irradiation capsule (or series of capsules) that is funded and controlled by the commercial graphite vendors and reactor designers, where costs and irradiation space within the capsule are shared. DOE supports such a collaborative approach and will fund the initial conceptual design through the DOE-ART program. Final design, fabrication, assembly, irradiation, and post-irradiation examination (PIE) costs would be shared among the commercial entities.

There is very limited space available for irradiation campaigns in the world's main MTRs (e.g., ATR, HFIR, and HFR-Petten), and the graphite vendors/reactor designers need the irradiation data as soon as possible. The most reasonable approach is for the vendors to collaborate on a single irradiation capsule design and to share the irradiation capsule(s) with limited specimen numbers of their specific graphite grades. That will provide the opportunity to gain (limited) data to determine the irradiation behavior of their specific graphite grade under reactor core conditions (e.g., temperature, He/Molten salt, irradiation dose, stress). Details concerning how such a collaboration can be successfully navigated are currently being discussed between the interested parties. Two face-to-face meetings have been conducted so far, one at ORNL in October 2022 and the other at INL in April 2023.

3.1 USA Material Test Reactor Availability

At these meetings, the strength and weakness of both MTRs within the USA were discussed. Due to the high demand for irradiated material studies, the availability of irradiation positions within both the HFIR and the ATR is severely limited. This corresponds to no more than one, possibly two positions, available for high flux graphite irradiation within each reactor for the foreseeable future. Each MTR can provide both drop-in (e.g., non-instrumented, no active temperature control, and limited mechanical load application) and active controlled (e.g., thermocouples, gas-mixture temperature control, and pneumatic mechanical load application) capsules. However, the differences between the two reactors make some types of experiments preferable to perform in HFIR, while a different set of experimental criteria would require the capabilities of the ATR.

Some of the primary differences between HFIR and ATR high flux irradiation positions are summarized below, with more details provided in Figure 2:

1. ORNL's HFIR high flux region positions:
   a) Nearly 6–10 dpa (maximum) per year
   b) Simpler irradiation conditions (single high flux region) result in more accurate dose estimations. Estimated dose error approximately ± 5%
   c) Smaller capsule volume due to 61cm active core height
      i) Smaller number of specimen within target flux trap (16mm diameter × 600mm long = total capsule volume of 485 cm^3).
2. INL's ATR high flux region positions:
   a) Nearly 5–6 dpa (maximum) per year
   b) More complex irradiation conditions (multiple high flux regions at once) result in less accurate dose estimations. Estimated dose error approximately ± 7%
   c) Larger capsule volume due to 122cm active core height
      i) Larger number of specimen within "B" irradiation positions (22.25mm diameter × 1200mm long = total capsule volume of 1865 cm^3).

During both meetings, experimenters from ATR and HFIR stressed that all types of irradiations experiments can be performed in either reactor. These include simple drop-in capsules, instrumented, and complex irradiation creep capsule designs. However, the capsule configurations will be different (e.g., capsule size, specimen size, flux levels, active instrumentation, active temperature control, and mechanical load applications, which all depend on specific core locations within the respective MTR). Therefore, depending upon the common requirements of the commercial vendors, either reactor would be a viable option so long as they agree on the irradiation conditions (e.g., environment, mechanically loaded vs. unloaded, active vs. passive temperature control). To provide examples of the capabilities for each reactor, two different capsule designs were presented at the meetings to illustrate some of the design challenges and potential solutions to graphite irradiation experiments. These are provided in the following sections.

3.2 Presented ATR VIC Concept

The ATR is the largest MTR in the world with over 100 possible irradiation positions located within and outside the high flux regions.

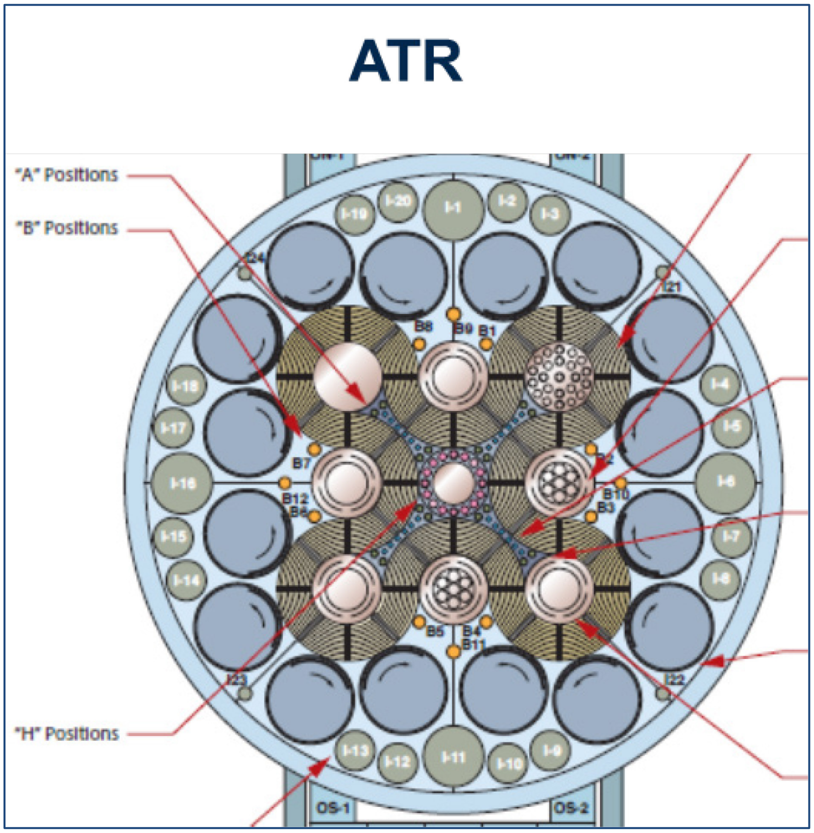

Figure 4. Irradiation positions within the ATR.

However, for practical purposes only three irradiation positions are considered likely in the foreseeable future (see Table 1). Obviously, the diameter of the core irradiation position is the critical parameter for determining whether instrumentation, active temperature control, or mechanical loads can be applied to the specimen within the capsule. Consequently, the inner "A" positions are most suitable for un-instrumented, "drop-in" capsule designs. Small "B" positions can have limited instrumentation, active temperature control, and possible limited mechanical loads on specimen. However, the large "B" is best suited for full instrumentation, temperature control, and mechanical loading of the specimen.

Table 1. Summary of likely ATR core irradiation positions for VIC experiment.

Position	Size, mm (inches)	Typical Flux (E > 0.1 MeV (10^{14} n/cm^2 · s)	Yearly Dose, dpa (EFPD *& Cycle Dependent)
Inner "A"	15.875 (0.625)	1.7	1.75–2 dpa/cycle
Small "B"	22.23 (0.875)	0.81	0.84–1.5 dpa/cycle
Large "B"	38.1 (1.5)	0.16	0.16–0.35 dpa/cycle

* Effective full-power days.

As there are a dearth of irradiation creep experiments planned, the primary ATR concept presented at these meetings is a hybrid design based upon the AGC and early Advanced Gas Reactor (AGR) capsules. This design would be a leadout-type experiment with a curved umbilical that exits the side of the reactor vessel through an “L” flange. The umbilical provides a pathway for the temperature control gas lines (helium/argon) and thermocouples from the ATR infrastructure to the capsule. This allows continuous monitoring and temperature adjustment by altering the gas mixture, which is capable of 100% helium, 100% argon, or any value in between. Additionally, one half of the samples will be under load during irradiation, while the second half will not. This is the same approach taken by the AGC program during irradiation.

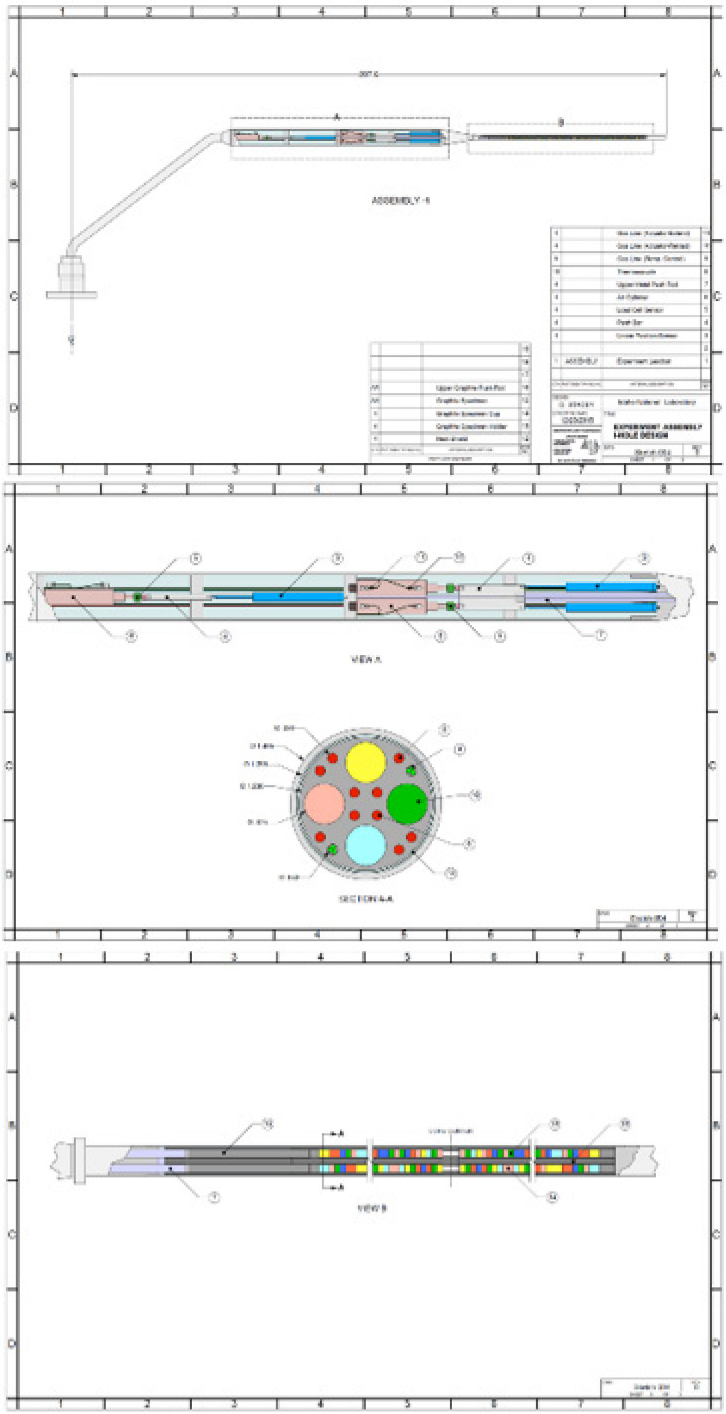

Figure 5. ATR conceptual VIC creep capsule design.

Due to the larger volumes available within the ATR "B" positions, the ATR VIC design can have active temperature control and pneumatic rams to provide a mechanical load to induce irradiation creep on a portion of the specimen. This requires a rather sophisticated gas control system to provide adequate gas flow and pressure to the capsule during irradiation. The ATR VIC experiment would use a gas control system similar to the AGC and AGR experiments (see Figure 6). This system can maintain temperature control within the 1200mm-long capsule up to 1000°C. The system can provide adequate pressure to the pneumatic rams to produce consistent mechanical loads up to 22 MPa on the graphite specimen.

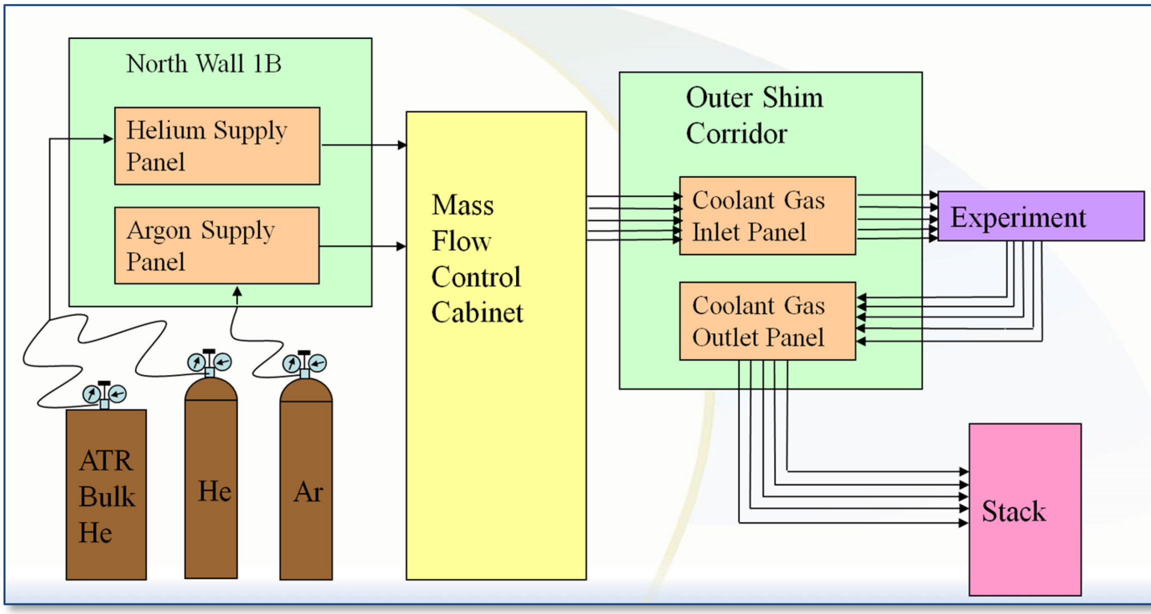

Figure 6. Illustration of possible gas control system for active temperature control and pneumatic rams to impose mechanical load for creep experiments.

3.3 Presented HFIR VIC Concepts

Two HFIR capsule designs were presented at the workshops based upon different locations within the HFIR core. There are tradeoffs to consider when deciding on the preferred location. The highest flux positions within the HFIR are located within the flux trap (center red region in Figure 7), but the flux trap is small; therefore, the maximum specimen diameter that would fit in a compressive creep capsule is 6 mm. There are only two locations within the flux trap that could accommodate the capsules as they would require ports in the pressure vessel head for feedthrough of electronics or deadweight for compressive loading, and the capsules are too small to include active temperature monitoring and control. The HFIR has much larger positions available in the reflector positions. These include the large removable beryllium facility (RB*) (green circles in Figure 7), the small vertical experiment facility (VXF) (orange circles in Figure 7), and the large VXF (large dark red circles in Figure 7).

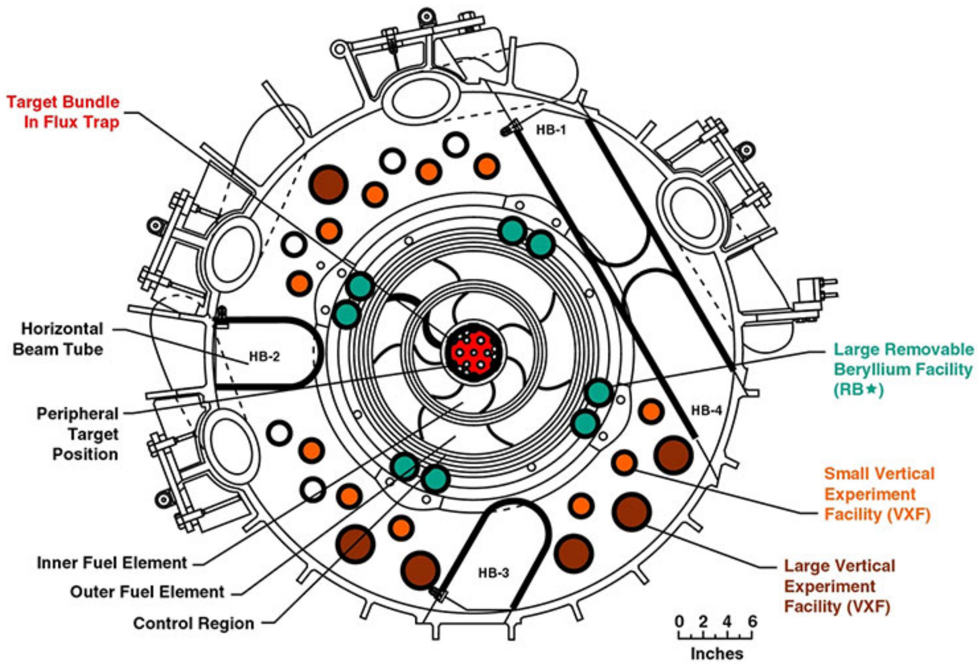

Figure 7. Cross section schematic of HFIR core (available at https://neutrons.ornl.gov/hfir/parameters).

These positions can accept more complex capsule designs and larger specimens, but there is a lower fast neutron flux and a larger neutron and gamma flux change over the reactor cycle. Therefore, a fully instrumented capsule with temperature measurement and control is necessary. The properties of these various irradiation locations are summarized in Table 2 and provide a comparison of the locations.

Table 2. Summary of HFIR core irradiation locations and relevant information for a VIC irradiation.

Characteristics	Flux Trap	RB*	Small VXF	Large VXF
Peak Fast flux, E > 0.1 MeV (10^{14} neutrons $cm^{-2}s^{-1}$)	11	5.3	0.5	0.13
Peak dpa per cycle, graphite	1.7	0.8	0.08	0.02
Typical capsule diameter (mm) Typical specimen diameter (mm)	13 6	43 25	37 20	69 40
Number of available positions for VIC	2	8	16	6

The choice of location for the VIC for the HFIR will be driven by the specimen size requirements. A capsule that is only irradiating *fine-grain* graphites (grain size <100μm) could be irradiated in the flux trap because specimen only have a 6 mm specimen diameter. An irradiation creep capsule for the compression of IG-110 has been already designed and used at ORNL [1, 2] (see Figure 8). The specimen had a diameter of 6 mm, the compressive load was obtained by a large block of tungsten as a deadweight (labeled as "upper weight" in Figure 8), and there was no active temperature monitoring or control. Larger specimen irradiations will have to occur in the reflector positions. A capsule was recently designed to irradiate tungsten materials in support of the U.S.-Japan fusion research program in an RB* reflector position. The capsule shown in Figure 9 will provide the starting point for the design of the graphite VIC for reflector positions.

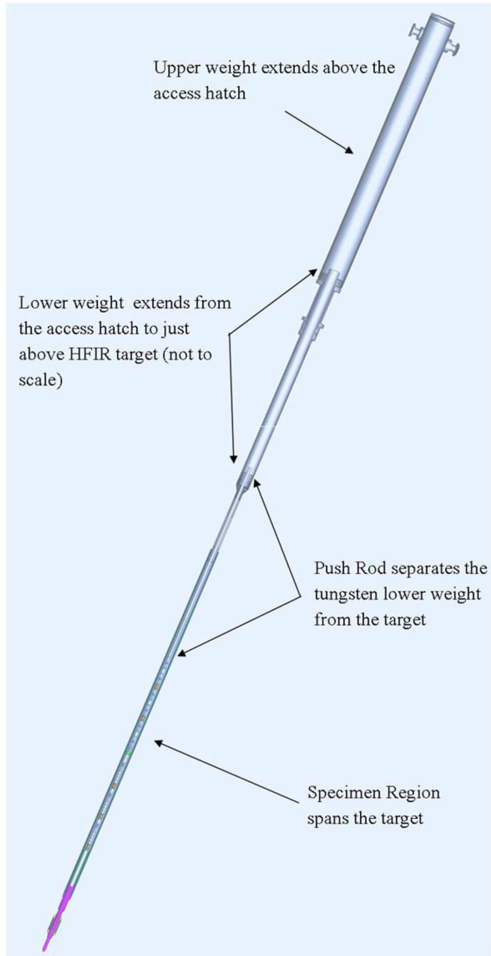

Figure 8. Schematic of IG-110 compressive creep capsule irradiated in the HFIR flux trap.

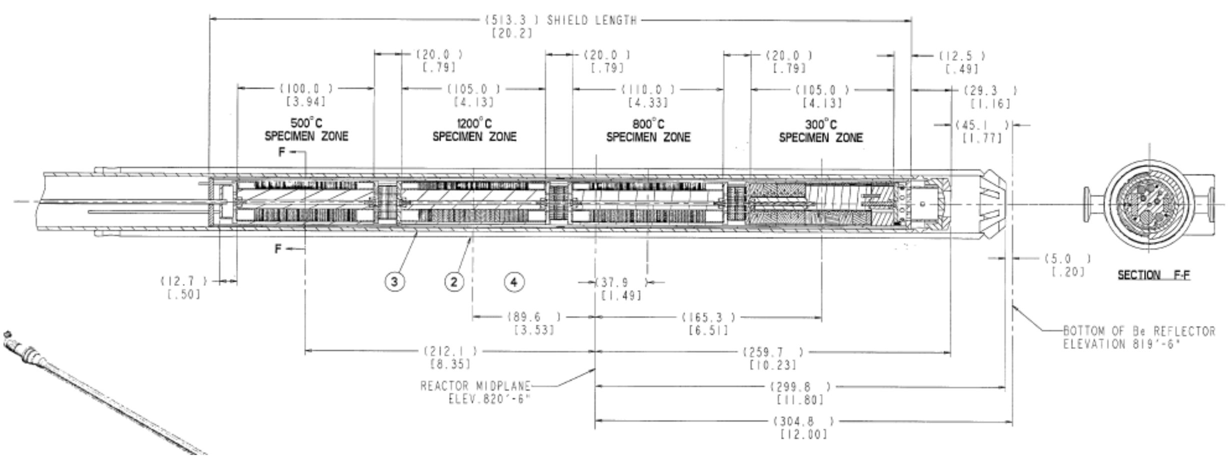

Figure 9. Drawing of the HFIR-MFE-RB-19J capsule (available at https://www.ornl.gov/division/rnsd/projects/hfir-mfe-rb-19j-materials-irradiation-experiment).

The internal configuration of the VIC will depend on the creep experiment desired by the reactor designers that are leading the effort. A preliminary tensile creep capsule was designed in the early 2000s by McDuffee and Burchell [3]. This tensile capsule was designed for a flux trap position, which is no longer feasible because of the demand for flux trap space, but the overall design can easily be modified to work in the RB* or other reflector positions. The compressive creep design from the IG-110 compressive creep program, however, can be easily modified for either the flux trap or a reflector position. The small diameter available for flux trap creep experiments will require the use of two capsules, one with stressed specimen and a second without load for reference specimen, whereas the reflector positions could most likely include stressed and reference specimen within a single capsule.

The final experimental support that is necessary for the VIC is the addition of extra capacity within the ORNL HFIR materials irradiation facility (MIF). The MIF is the heart of any instrumented irradiation capsule but requires access to leadouts from ports on the top of the HFIR pressure vessel (Figure 10). The MIF includes temperature monitoring via thermocouples, temperature control via changing gas mixture, the application of load through bellows pressure control, and displacement tracking with linear variable differential transducers. The instrumentation and control for a single experimental capsule is in a control cabinet. The MIF currently has one operational control cabinet; however, a second control cabinet is ready for assembly. It is expected that two cabinets would be needed to support the VIC, so the focus for near-term VIC support will be assembling and dedicating the second MIF cabinet and developing a cost estimate for the construction, assembly, and dedication of a third MIF cabinet.

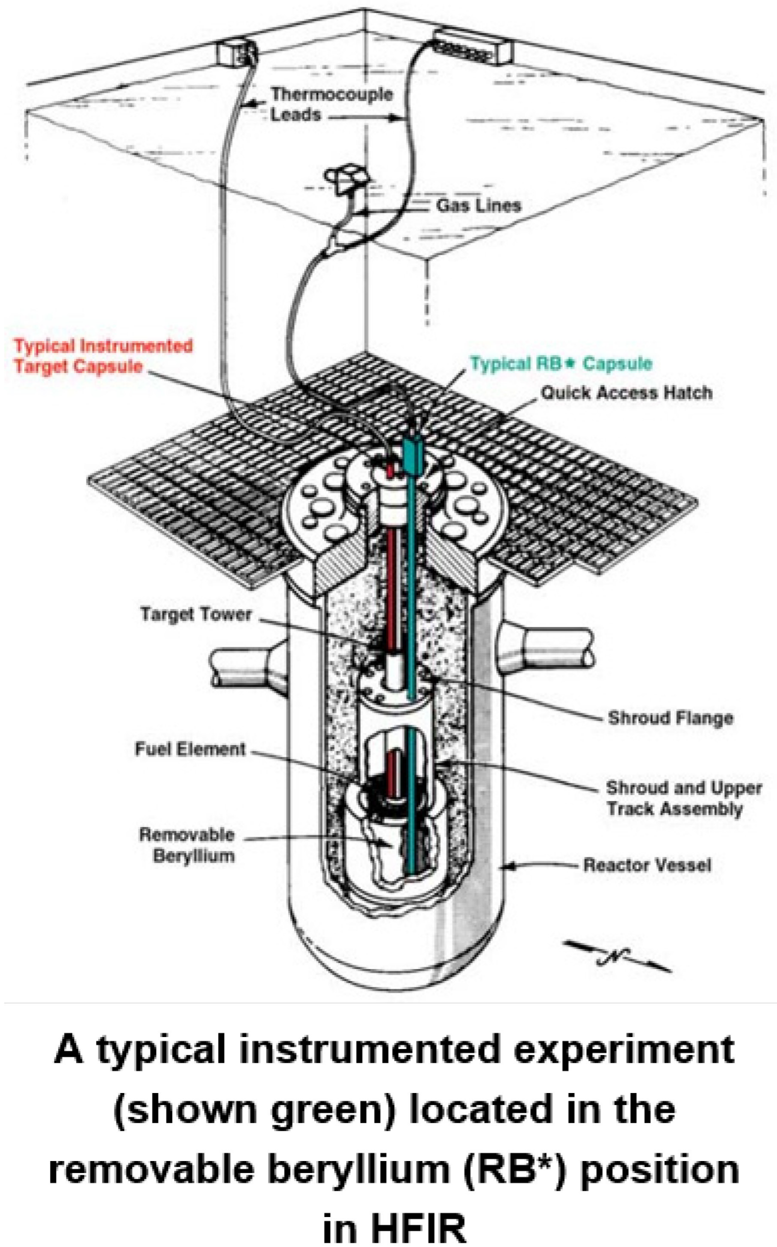

Figure 10. Schematic representation of leads extending from the top of the HFIR pressure vessel for a flux trap (red) or RB* (green) positions (available from https://www.ornl.gov/division/rnsd/projects/materials-irradiation-facility-mif-materials-and-fuels-irradiations).

3.4 Proposed Schedule

It was impressed upon the vendors that material irradiations are not quick or inexpensive. The complexities and high-cost infrastructure associated with handling irradiated materials and the resulting high radiation activity levels make these experiments very difficult to perform. Based on their experience, INL and ORNL irradiation experts presented the expected duration period anticipated for a “typical” commercial irradiation capsule (see Figures 11-14). Figure 11 illustrates simplistic schedules based on the highest flux positions available within the HFIR and ATR to illustrate that even for the highest flux positions, the irradiations will take years to achieve even the lowest dose level irradiations.

3.4.1 Design and Irradiation

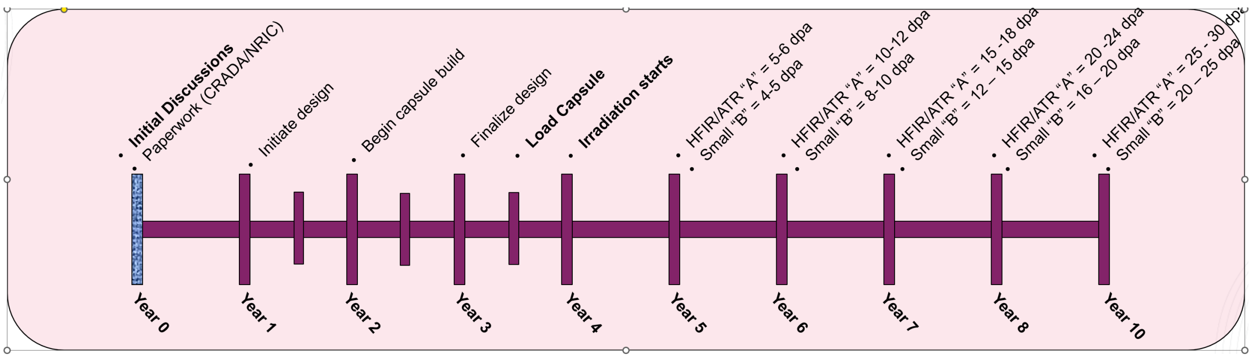

Figure 11. Proposed schedule for HFIR and/or ATR irradiation campaign(s).

3.4.2 Post-Irradiation Examination (PIE) Schedule

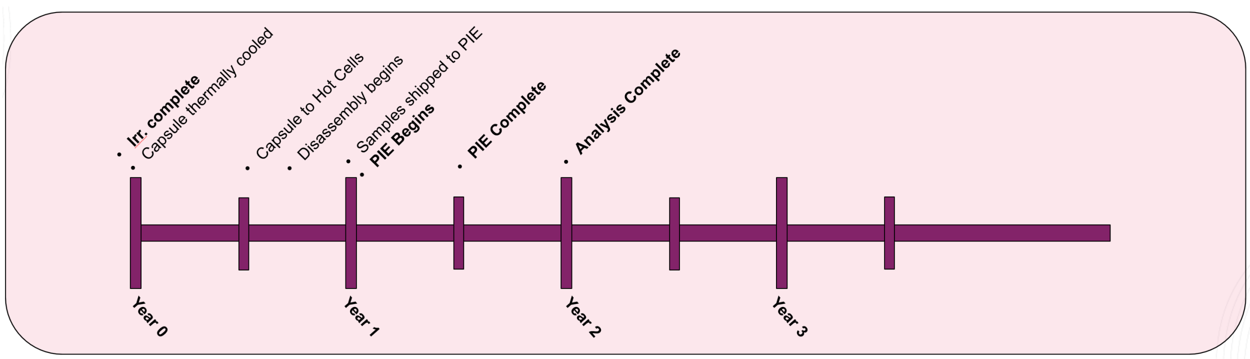

Figure 12. Proposed PIE schedule for graphite specimen testing.

3.5 Irradiation Positions in ATR and HFIR

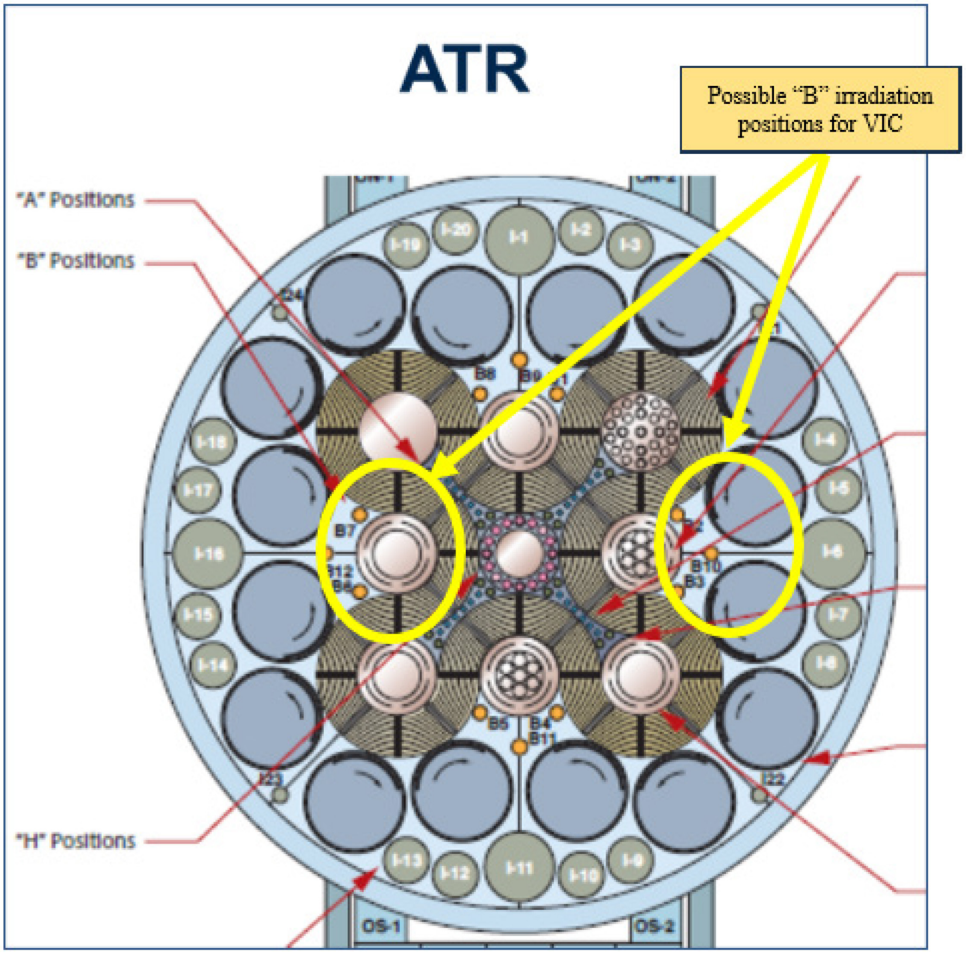

Figure 13. Possible "B" irradiation positions within ATR for VIC experiment.

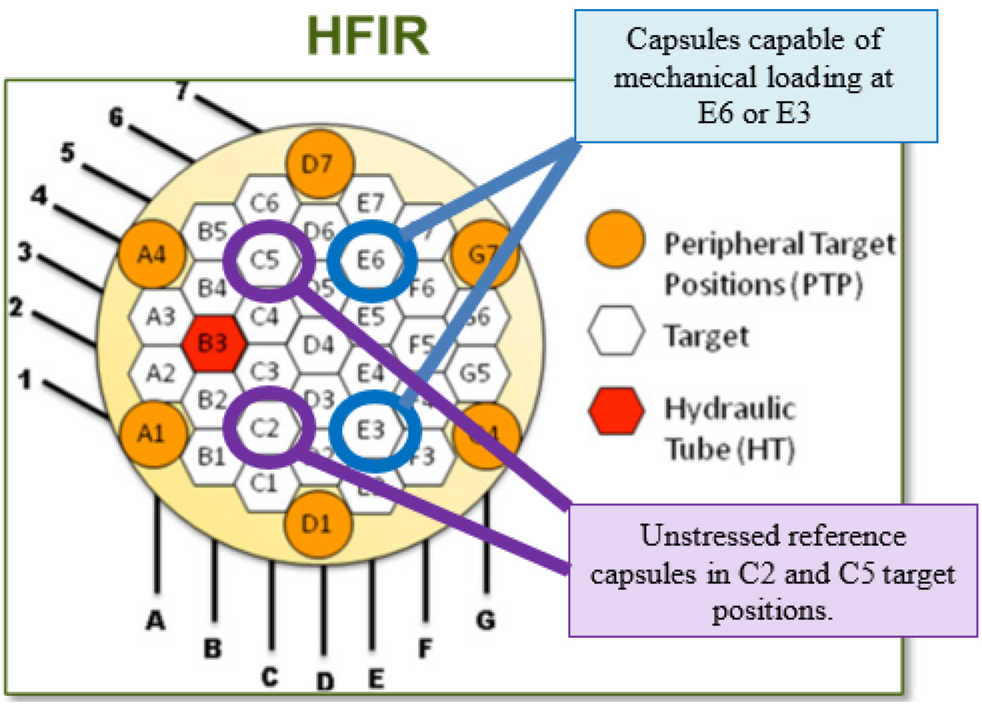

Figure 14. Possible irradiation positions within HFIR target bundle in flux trap.

3.6 Costs

For this type of endeavor to be successful, particularly with DOE unavailable as a backstop, competitors need to be able to collaborate. While there is interest in moving forward with this collaborative model within the commercial graphite vendor/reactor designer communities, currently no vendors have agreed to collaborate on the design or cost sharing of a common irradiation capsule. Though this conversation is in its infancy, time is of the essence, and there are issues that will need to be addressed to keep this effort moving forward. The prospect of losing intellectual property advantage to their competitors is keeping the vendors from agreeing to share experimental costs and data. However, the vendors are beginning to understand that the long time periods associated with irradiation and PIE combined with the limited space in the MTRs may require collaboration.

The monetary investment necessary for an irradiation campaign is not s=insignificant. Spreading the cost for a common irradiation capsule will certainly make such a collaboration more palatable, but there are details that will need to be worked out. For example, a scenario that is important to evaluate is what happens if one of the partners drop out mid-stream. DOE will not cover the remaining balance; it would be the responsibility of the collaborators. Provided below is a rough-order-magnitude estimate of the costs for this capsule:

- Initial design – $800K (provided by DOE)
- Final design –- $250K
- Fabrication –-- $650K
- Assembly –--- $400K
- Irradiation –---- $1.5K per cycle

- PIE – $1M+
- ATR infrastructure (temperature/load control systems) – $1.5M
- HFIR Infrastructure – N/A.

4. CONCLUSIONS

During FY 2023, two VIC collaboration meetings have been held. The first collaboration meeting was held at ORNL in October 2022. The meeting minutes and conclusions were summarized within ORNL/TM-2023/2945 “Summary of Vendor Irradiation Capsule Workshop Hosted at Oak Ridge National Laboratory, October 3–4, 2022.” Information from the second collaboration meeting held at INL April 2023 is summarized in this report.

The DOE researchers expended a great deal of effort to demonstrate that graphite irradiations are complex, expensive, and time consuming and to demonstrate that performing graphite irradiations is complicated due to the few positions available within the three primary MTRs (worldwide) used for material irradiations. After presenting several HFIR and ATR irradiation capsule designs that have similar irradiation conditions (i.e., temperature, dose, coolant, creep, etc.) that could be shared between several vendors, the concept of vendors collaborating by combining their specific graphite specimen in common irradiation capsules was discussed. Conclusions and future actions from this discussion by commercial HTR designers, graphite suppliers, and DOE researchers are summarized in Appendix A, “ Vendor Interest.”

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Appendix A

Vendor Interest

At the conclusion of the April 2023 meeting, the consensus of all participants was a general (if cautious) agreement of a collaborative, cost-sharing irradiation capsule. Several issues were raised that need to be addressed by DOE, commercial vendors, and graphite suppliers. These issues, along with several others, will be collated within a letter of inquiry, which will be distributed in early 2024 to the U.S. DOE-NE and the upper management of each participating vendor/graphite supplier. The responses and subsequent follow-up activities will be compiled and discussed in a future report in 2024.

These first issues of concern are outlined below. A letter of inquiry is currently under draft and will be issued to participants for comment once it has been finalized. These topics will be clarified and expanded upon to provide the DOE and vendor management with enough information to determine whether to proceed with this concept or to table it for future action.

A-1. Letter Outline for Vendor Irradiation Capsule (VIC) Concept

1. Premise: Commercial vendors (HTR designers and graphite suppliers) pay for a common irradiation campaign.
   a) Commercial vendors jointly pay for one (1) drop-in capsule at HFIR and one (1) creep capsule in ATR and share the information.
      i) This will be a "universal" capsule design.
      ii) Where does HFR (Petten) fit in to this collaboration?
   b) This activity should be designed to work with the ASME initiative for "all graphite grades to behave the same up to turnaround dose": justifying limited individual data (vendor specific graphite) by using the general pool of irradiation data from all grades.
   c) <u>Primary benefit</u>: This takes irradiated graphite issues off the table for all parties, including reactor designers, graphite vendors, DOE, and even NRC. Since irradiation time and room within MTRs is limited for the foreseeable future, this will provide as much data as possible to complete the initial design requirements for nearly all concepts. While it is understood that this will not provide a complete irradiated dataset to qualify even a single graphite grade for all potential operating temperatures and neutron dose levels, it must be recognized that the possibilities for more irradiated data are extremely limited for the next 10 or more years due to limitations within every MTR worldwide.
   d) <u>Assumptions</u>:
      i) It is assumed that the data from these capsules will provide enough irradiation data required for initial licensing requirements for nearly all designs.
      ii) DOE cannot commit to picking up the funding if one of the collaborators cannot meet their obligations.
2. Need a written draft proposal or letter from INL/ORNL to vendors/graphite suppliers (early 2024)
   a) What is proposed scope?
   b) What is the rough cost?
   c) What is the time schedule?
   d) What are the deliverables and commitments from all participants?

i) **Commercial**: Commits to providing material, capsule, and irradiation cost share and to sharing data.

ii) **DOE**: Commits to providing subject matter experts and general support (personnel and facilities) for irradiation testing:

(1) Irradiation priority, disassembly capabilities, shipping capabilities, PIE capabilities, etc.

iii) **Primary Deliverable**: A set of data (irradiation material property changes and creep) at three different temperatures.

e) How does this activity work with ASME and NRC expectations?

f) Risks that may occur:

i) This is a long-range experiment that will take many years.

ii) What happens if a collaborator drops out?

(1) Will DOE step in to complete the irradiation experiment(s)?
(2) Will DOE stop irradiations if one collaborator drops out?
(3) Will DOE continue to prioritize commercial graphite irradiation?
(4) Will other collaborators be responsible for the additional (lost) funding to continue the experiment?

3. Issues with this concept

a) Joint Development Agreement – legal hurdle for this concept

b) Potential mixing of DOE color of money

c) What if a collaborator runs out of money before the completion of experiment?

d) Will require DOE to support this activity in general (no funding)

e) Technical issues:

i) What about differences in grain size, fabrication methods, sample size requirements?

ii) Temperature limits (lower and upper bounds)

(1) Active control vs. passive
(2) Instrumented (TC) vs. un-instrumented (silicon carbide [SiC] or melt wires)

iii) Creep capsule and drop-in capsule requirements.

4. Time scales

a) If getting this agreement takes too long (>24 months), then the deal is off.

b) Follow-up meeting will be held in the first part of 2024.