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Current and Future Technological Issues Challenges for Nuclear Graphite Components

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Changing the World's Energy Future

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Idaho National Laboratory

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Current and Future Technological ~~Gaps~~ for Nuclear Graphite Components

- Issues
- Challenges

Idaho National Laboratory

Talking points

- **Historical and current data requirements for component qualification**
  - As-manufactured graphite material properties
  - Irradiated & degraded material issues
    - ***The good, the bad, the ugly***
- **Code rules – Construction & Operation**
  - Status of current ASME code rules
    - ***Progress in Design rules***
    - ***Degradation***
    - ***Construction vs. Operation***
- **What should we be planning to do?**
  - New technical areas getting started
  - We need to be serious about Nuclear Graphite

NEW OLD

My Apologies to INGSM 2023 (and Tony Wickham)

- I left meeting with a list of problems …
- … without solutions

- Let's look at some potential solutions and activities to address these issues
  - ***USA & Intn'l research***
  - ***ASME, IAEA, & ASTM activities***
  - ***Industry activities***

From "Status and Lessons Learned from the DOE Graphite Qualification Program", INGSM 2023, 10th – 14th September 2023, Aachen, Germany

My Concerns

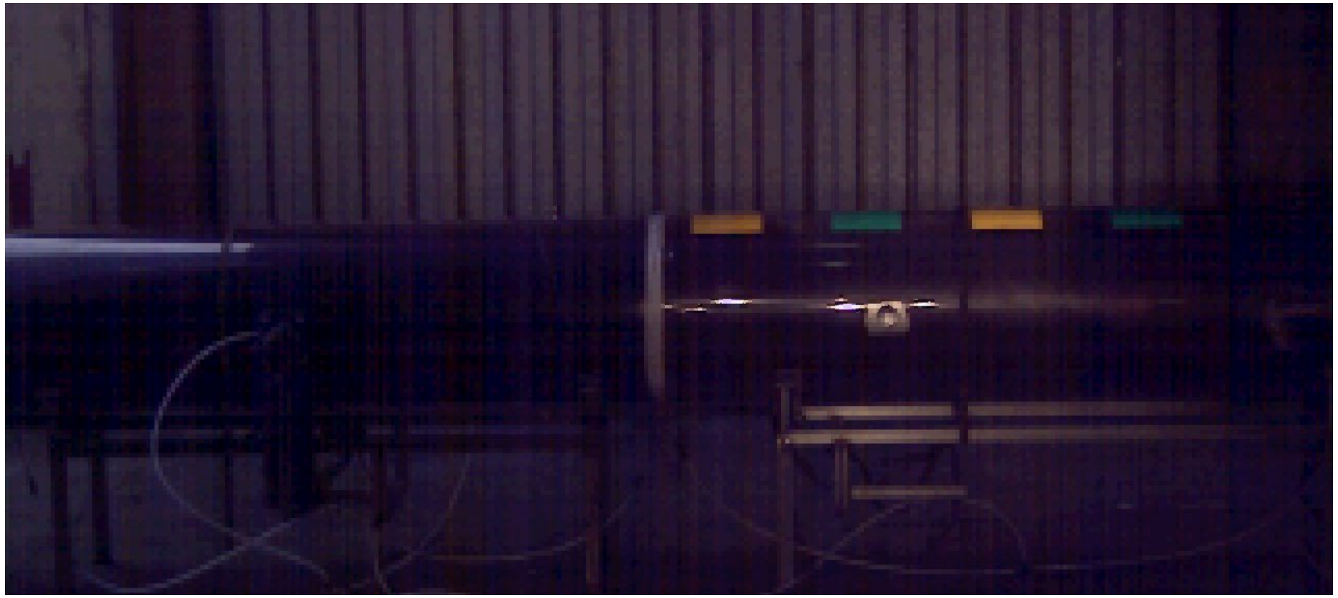
1. Not enough irradiation data (world-wide problem)
2. Specimen sizes → they keep getting smaller. Why?
3. Molten Salt Reactors → Entire industry based upon a 3-year experiment. 60 years ago
4. Weaponization of data → Commercial reactors not collaborating (sharing data)
   - *Why privately funded sensitivity studies for D8289!?!*
5. Behavior models will be critical to assist in predicting component lifetimes
6. Kicking the can down the road:
   - *Lack of **Vendor/Supplier contributions** to ASTM and ASME*
   - *Inspection → acknowledging the need for frequent inspections on first builds*
   - *Waste issues*
7. Lack of ASTM standards for degraded material → Molten salt testing?
8. Still don't know why graphite behaves the way it does.

20

Let’s start off with the easy stuff

- **Graphite Fires do not occur**
  - Proven analytically and experimentally
  - It oxidizes, sure. But no sustained fire
  - Several recent papers, reports, and new ASME technical document as reference

Graphite at 1000°C



Graphite Dust (not) exploding

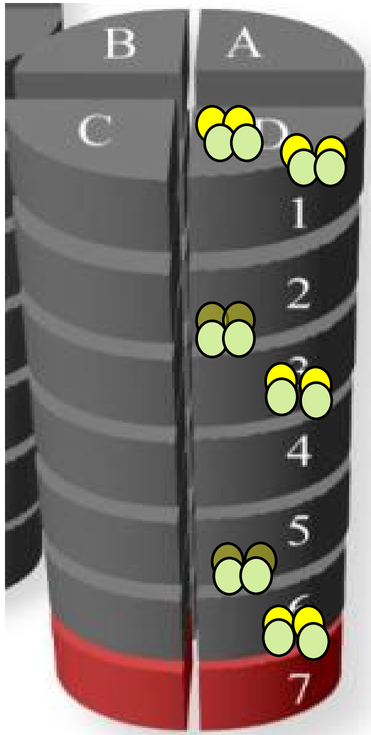
- **Graphite dust does not explode**
  - Proven analytically and experimentally
  - Initial “spark” is RSA sites on dust surface
  - But once they are gone it self-extinguishes

Next: Need to qualify new grades

PGA
Gilsocarbon
H-451
ATR-2E

- Historical graphite grades aren’t available
- Find a suitable grade
  - Near-isotropic & low impurity grades – common for all “nuclear” grades
  - All other material property values are left to the Designers to decide
    - *Where is the data needed for Designers?*
    - *Who is responsible for getting the data?*
  - Proper Quality Assurance (QA) for manufacturing
    - In USA this is NQA-1. *Not been implemented for graphite manufacture in 40+ years*
    - Unirradiated material properties are needed for initial core design and construction
    - NQA-1 testing plan for measuring material properties within the grade
- These questions are currently being resolved several different ways
  - Designer-to-Manufacturer – *Responsible owner of data & NQA-1 implementation*
  - Changes to 2025 ASME BPVC – *Multiple code changes last 2 years*
  - DOE reviews of prototypes – *NQA-1 and ASTM questions*

Need the (unirr) data for initial core design?



ASME minimum sample population ~ 300

- Basically, a lot of material property testing is needed
  - Must determine the inherent variability within the grade
    - ***Intra-billet, inter-billet, and Lot-to-Lot variability***
  - Large tensile strength population is critical for ASME
- Can you use previous material property data? NQA-1 question
  - Yes. Sort of. It depends. → Being sorted on case-by-case
- Mostly well spelled out in ASME code and ASTM standards
  - ASME and ASTM have defined minimum requirements
    - ***But there are some discrepancies in ASTM D7219 and ASME BPVC***
  - Serious research has been expended in this area (USA and Intn'l)
    - ***New ASTM test standards developed over the past 30 years***
- This is where most of the USA designers/suppliers are right now
  - Need to decide ***who*** will get this data

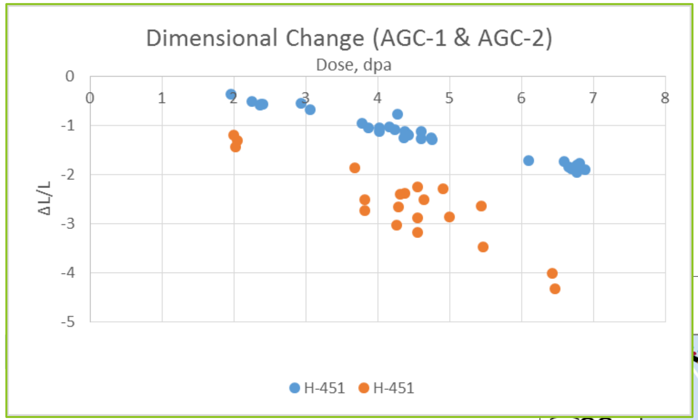
Baseline: Unirradiated Material Properties

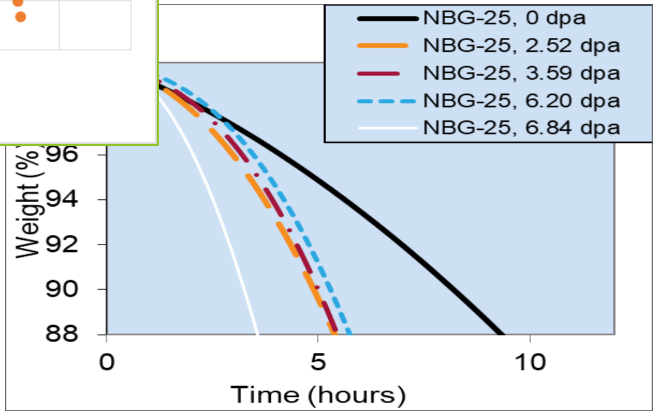
- Five major graphite grades
  - Multiple Billets
    - ***Some different lots***
  - Has 30,000+ data points
- No grade completely tested
  - That's for commercial sector to perform
- All data NQA-1 conforming
- Available on NDMAS
  - *https://ndmas.inl.gov/SitePages/NDMAS_Pages_Home.aspx*
  - New administrator:
    - **courtney.otani@inl.gov**

Graphite	Laboratory	Billet #	Percent Complete					
			Machining	Mass and Density	Elastic Testing	Mechanical Testing	Thermal Testing	Split Disc
PCEA	ORNL	XPC01S8-11	100%	100%	100%	100%	100%	
PCEA	INL	XPC02S8-7	100%	100%	100%	100%	100%	
PCEA	INL	XPC01S8-9	100%	100%	100%	100%	100%	
PCEA	INL	XPC02S8-5	100%	100%	100%	100%	100%	100%
PCEA	INL	XPC01D3-35	50%					
PCEA	INL	XPC01D3-36	100%	100%	100%	100%	100%	
NBG-18	INL	635-4	100%	100%	100%	100%	100%	
NBG-18	INL	635-14	100%	100%	100%	100%	100%	
NBG-18	ORNL	635-6	100%	100%	100%	100%	100%	
2114	INL	A20568	100%	100%	100%	100%	100%	
2114	INL	A20570	100%	100%	100%	100%	100%	
2114	ORNL	116310	100%	100%	100%	100%	100%	
NBG-17	INL	830-3	100%	100%	100%	100%	100%	
NBG-17	INL	V104	100%	50%		50%		
IG-110	INL	089052-7	100%	100%	100%	100%	100%	
IG-110	INL	10X69	100%	100%	100%	100%	100%	

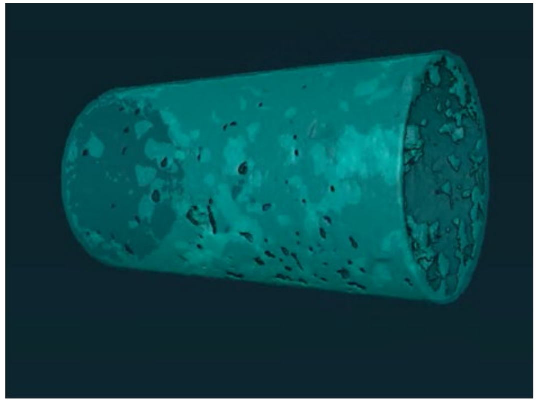
Degradation Challenges

- Irradiation
  - What data is available? What is missing?
  - Before and after turnaround dose material
  - Moving forward :
    - *Irradiation programs (AGC, private irradiations, VIC)*
- Oxidation
  - What is known about graphite oxidation? Acute vs. chronic
    - ***Significant** progress in last 20 years*
  - Irradiated oxidation rates, oxidation penetration and microstructure
  - What challenges remain to be answered for oxidation
    - *Purification, irradiation dependency, acute vs. chronic oxidation, etc.*
- Molten salt
  - What is being researched and what has been discovered in the past 2-3 years.
  - Moving forward:
    - *Chronic vs. acute. fluorination or other chemical attack, galvanic coupling*
- Other degradation challenges
  - Wear, abrasion, dust





Increased oxidation rate of irradiated graphite

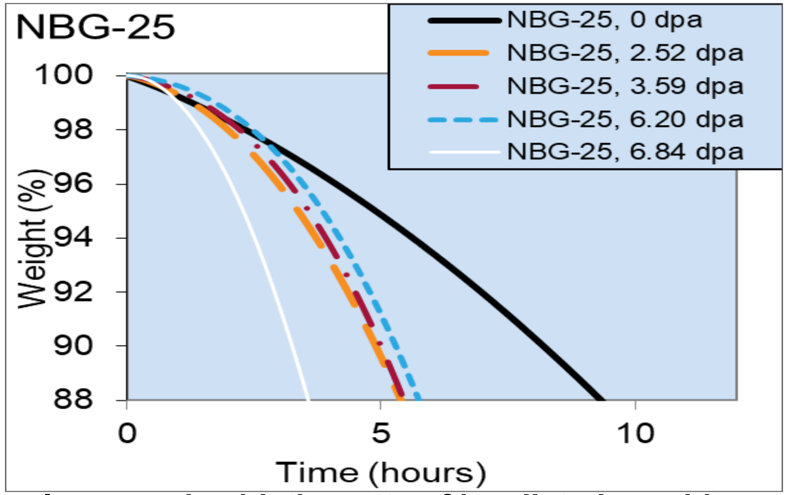


Tomography of NBG-18 sample exposed to molten FLiNaK, 3 bar, 750°C, 336 hours

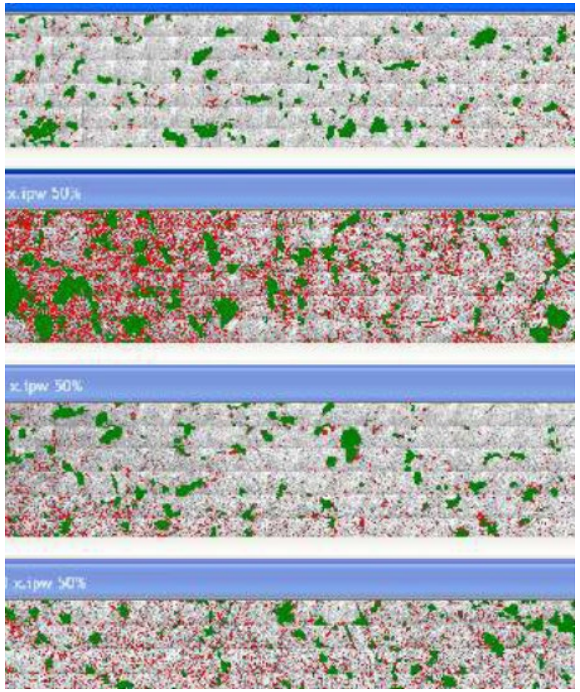
Oxidation Degradation

- A huge amount of progress in last 20 years
  - We know thermal oxidation like never before
- ASTM Standard (D7542) has been critical
  - We now have a baseline to compare different grades
  - Nearly all major grades of interest have oxidation rates
  - We can assess additional degradation mechanisms
    - ***Strength after oxidation, oxidation after molten salt, irradiated graphite***
- Most of the **acute** issues for design and construction are set

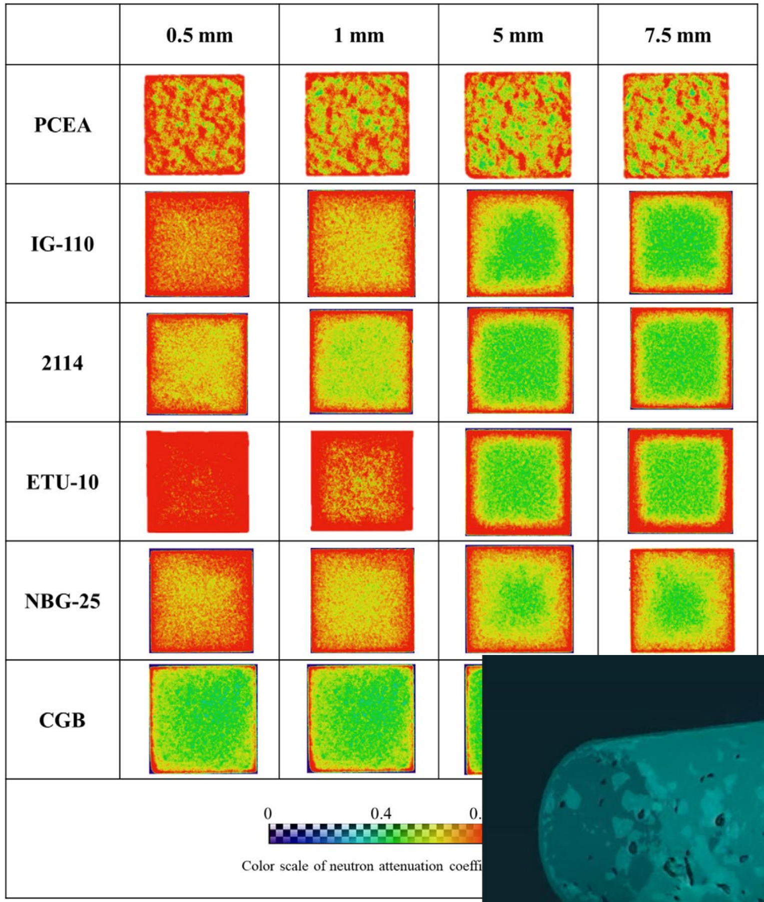
- Ongoing issues – moving forward
  - Component response (vs small specimen)
  - Chronic oxidation during normal operation
    - ***Operational degradation – More later in ASME***
  - Combined degradation: oxidation of irradiated graphite



Increased oxidation rate of irradiated graphite



Molten Salt



Tomography of NBG-18 sample exposed to molten FLiNaK, 3 bar, 750°C, 336 hours

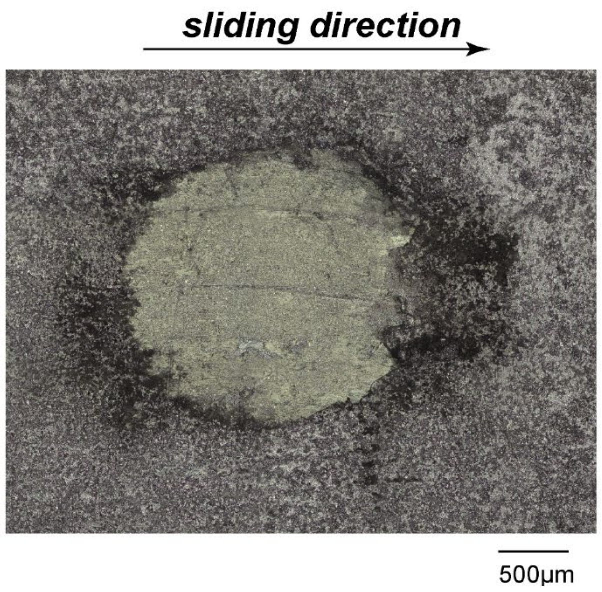
- A huge amount of progress in last **five** years
  - Initial acute fears are not as bad as imagined
    - ***Molten salt intrusion – stress concentrators***
    - ***Wear, abrasion, erosive chemical attack by MS***
- Developing new procedure and ASTM Standards
  - Difficulties in deciding “blind” in-situ or post exposure testing
  - New FLiBe testing capabilities are coming on-line
- Ongoing issues – moving forward
  - Must still verify initial acute results
  - Chronic issues must be addressed
    - ***Fluorination of carbon still to be determined***
    - ***Galvanic coupling questions still to be resolved***
  - Operational degradation – More later in ASME

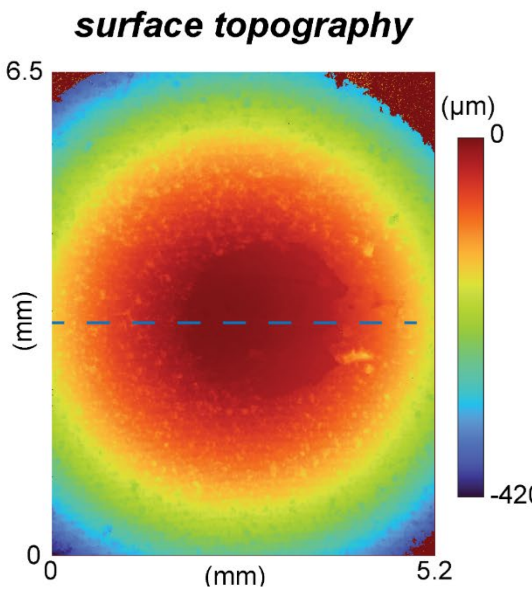
Other Degradation challenges

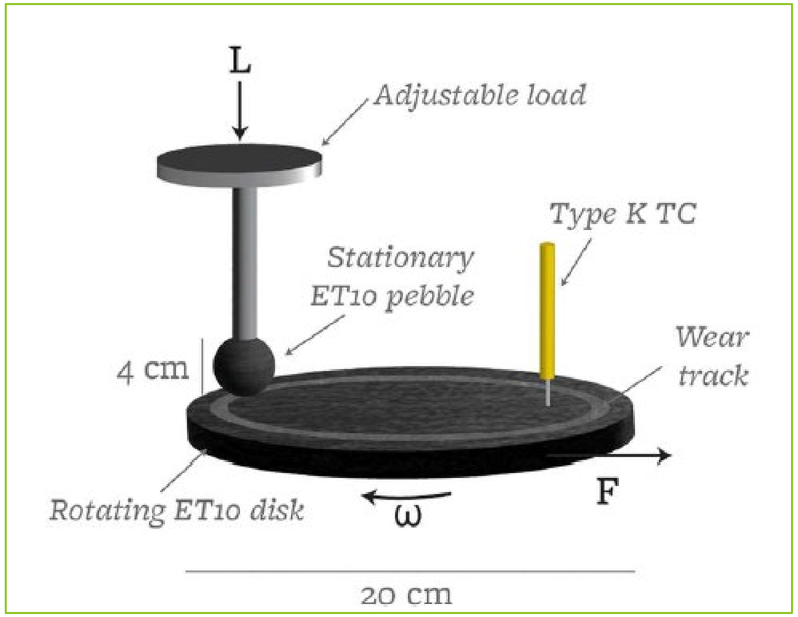
nm/s

- Abrasion, erosion, surface damage - dust
  - Initial results indicate no big show-stoppers
  - Molten salt environment not as bad as initially imagined

- Early days – more to come

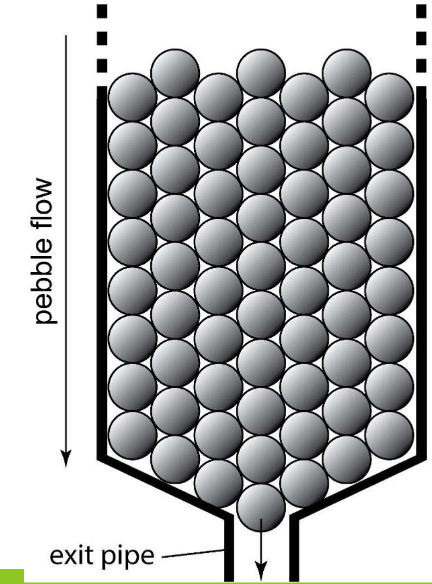






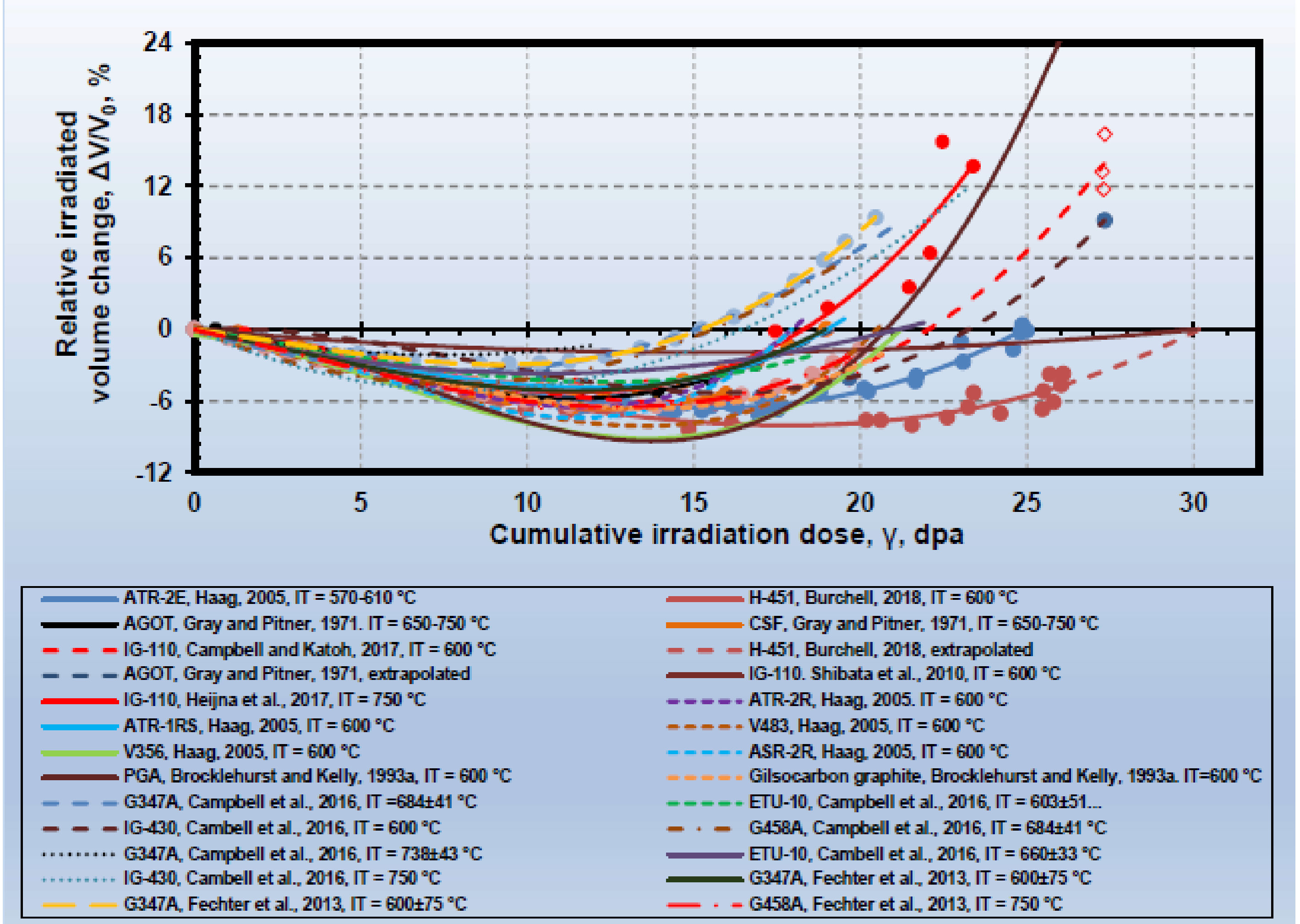
- Ongoing issues – moving forward
  - Need to confirm initial results

- Getting the conditions correct is a challenge
  - Need to work with commercial Rx to confirm operating conditions



And the big one … Irradiation

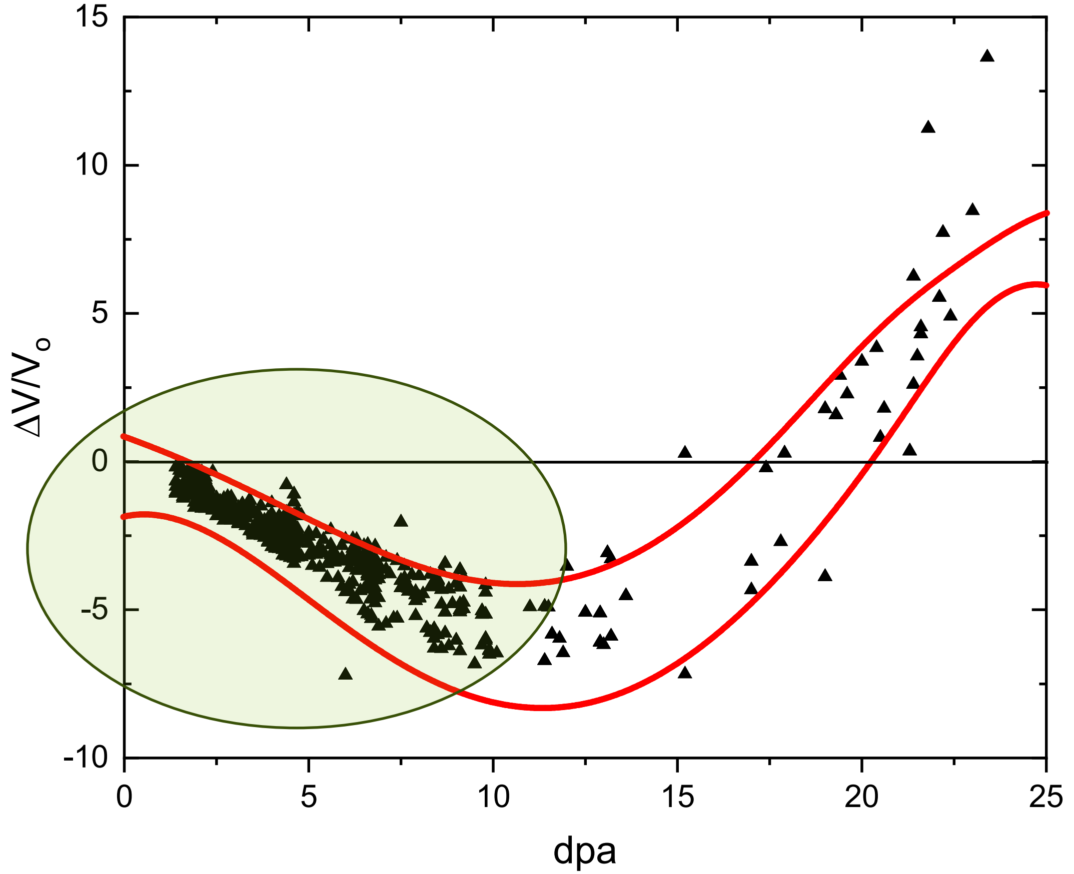
- Lots of data
  - More data than Alloy 617
    - *Recent ASME code case*
- Problem is multiple grades
  - And we have no idea what makes them act differently
  - Not a clue



Dr. Makuteswara Srinivasan, "Perspective on Irradiation Dimensional Change of Graphites", INGSM 2021,

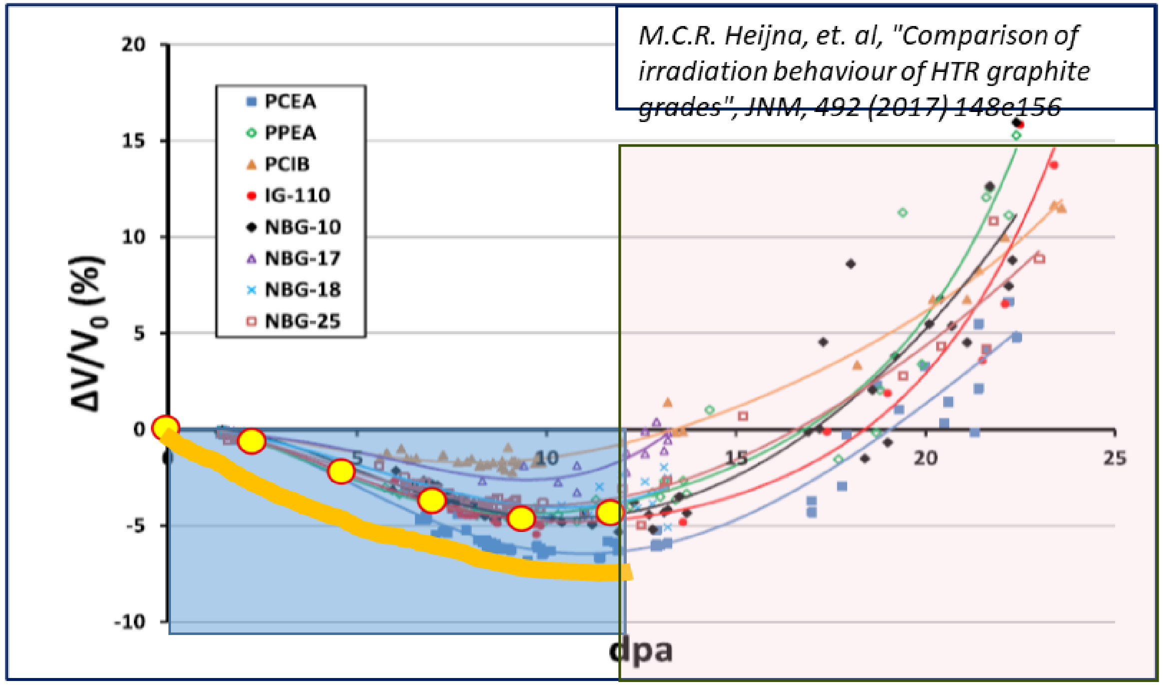
- What to do?
  - Do we need more data?
  - No more national Irradiation programs
  - ***Nationals provided initial data trends***
- Private industry must step up now
  - How?

Leveraging the existing data: Short term operation



Commonality of irradiation response already been recognized:

(pre-turnaround)

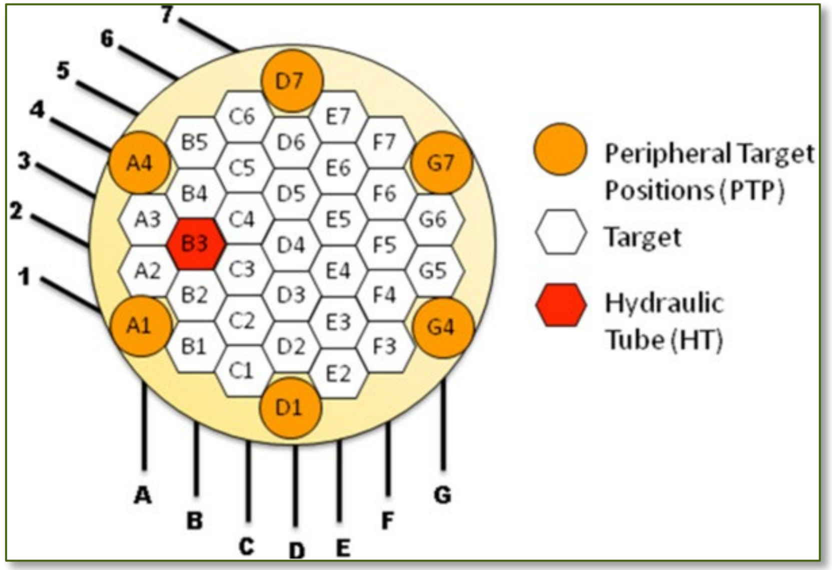


What if more data is needed?

- **_Post-turnaround_**
- **_Different temperature range_**

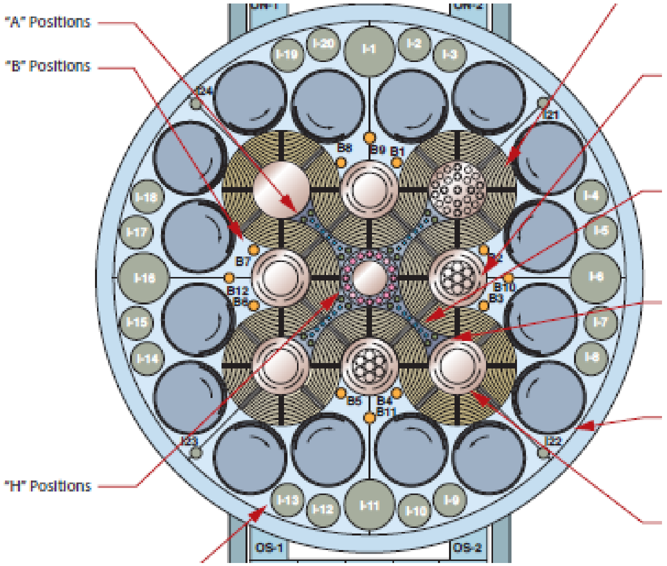
New irradiation data - MTRs that are available

HFIR



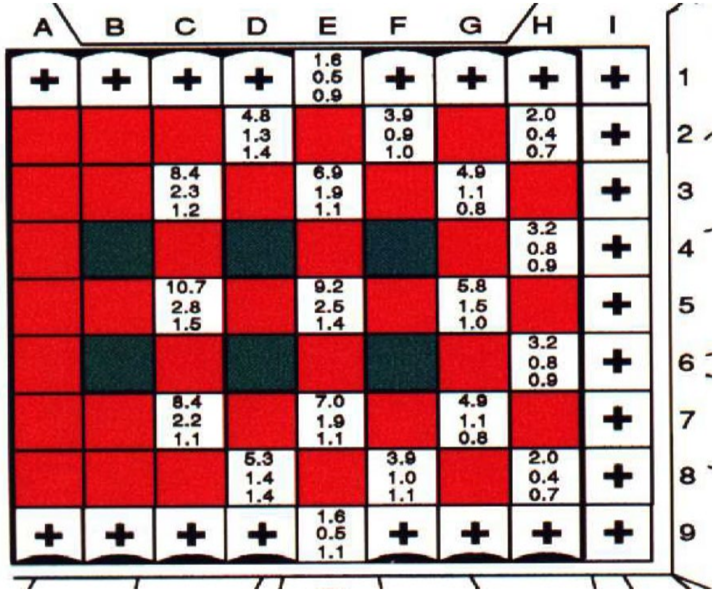
- *61cm (24inch) height*
- *30 target positions (2 can be instrumented).*
- *6 peripheral target positions*
- *Rabbit*
- ***Nominal diameter ~ 1.8cm (5/8")***

ATR



- *123cm (48inch) height*
- *9 flux traps, 68 core positions*
  - *Instrumented > 0.625*
- *Rabbit*
- ***Diameters range:***
  - *1.6cm (0.625")*
  - *2.2cm (0.875")*
  - *13.5cm (5.375")*

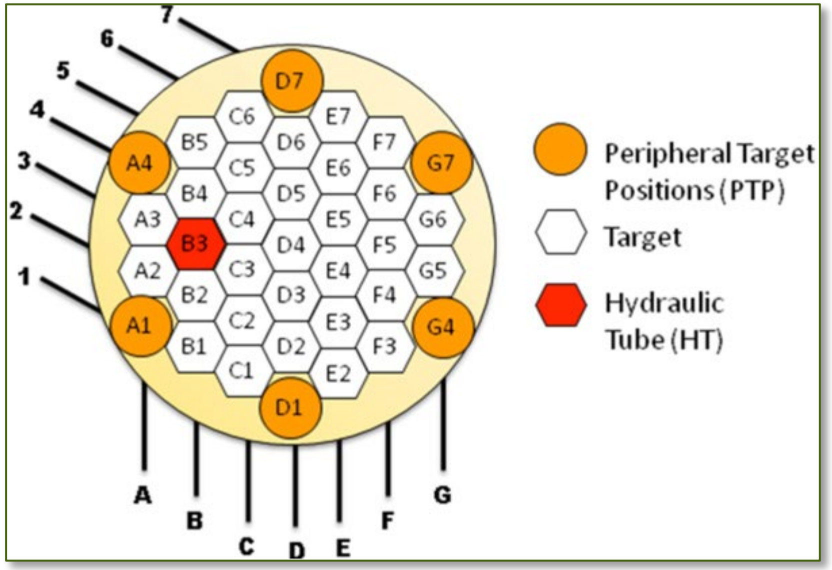
HFR (Petten)



- *60cm (24inch) height*
- *17 experimental positions*
- *Rabbit*
- ***Nominal diameter ~ ??***

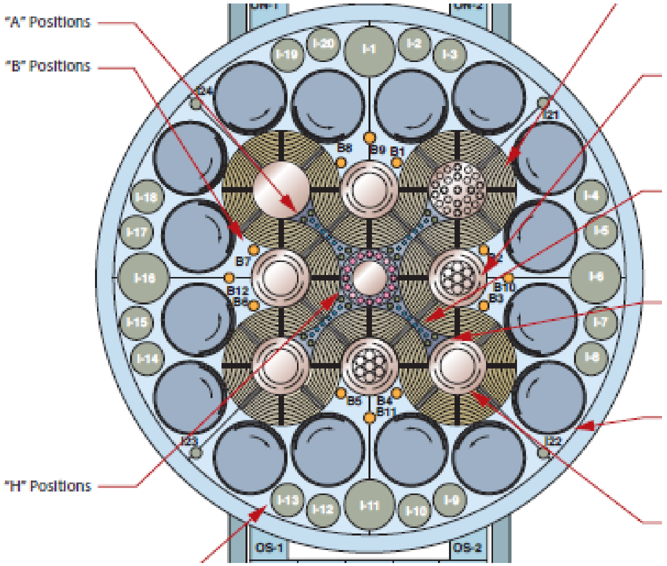
Realistic Irradiation positions in those MTRs

HFIR



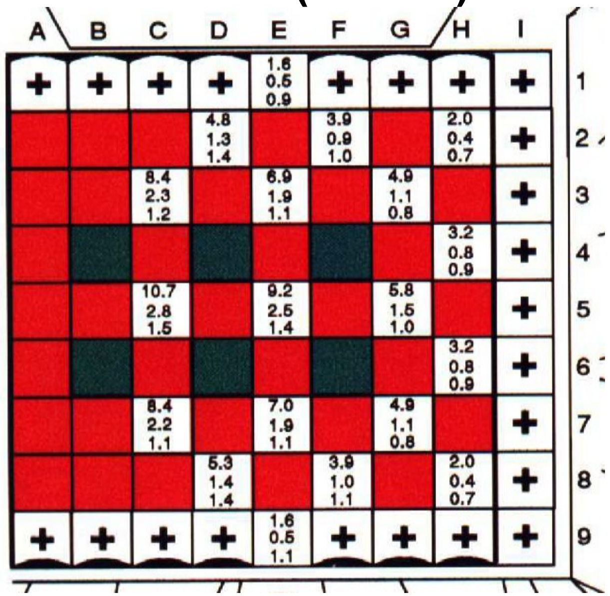
- ***1-2 target positions*** *= 1.8cm (5/8")*
  - *Instrumented?*
  - *Likely Passive*
- *Flux ~ 2 x 10^{15} n/cm^2· s*
- *Total yearly irradiation:*
  - *~ 24 day cycle*
  - *~ 5-6 Cycles per year*

ATR



- ***"A" positions = 0.5" & 0.625" or***
- ***Small "B" positions = 0.875"***
  - *Instrumented = "B"*
- *Flux ranges:*
  - *Small "A" ~ 2.3x10^{14} n/cm^2· s*
  - *Large "A" ~ 1.7x10^{14} n/cm^2· s*
  - *Small "B" ~ 8.1x10^{13} n/cm^2· s*
- *Total yearly irradiation:*
  - *~ 60 day cycles*
  - *~ 4-5 cycles per year*

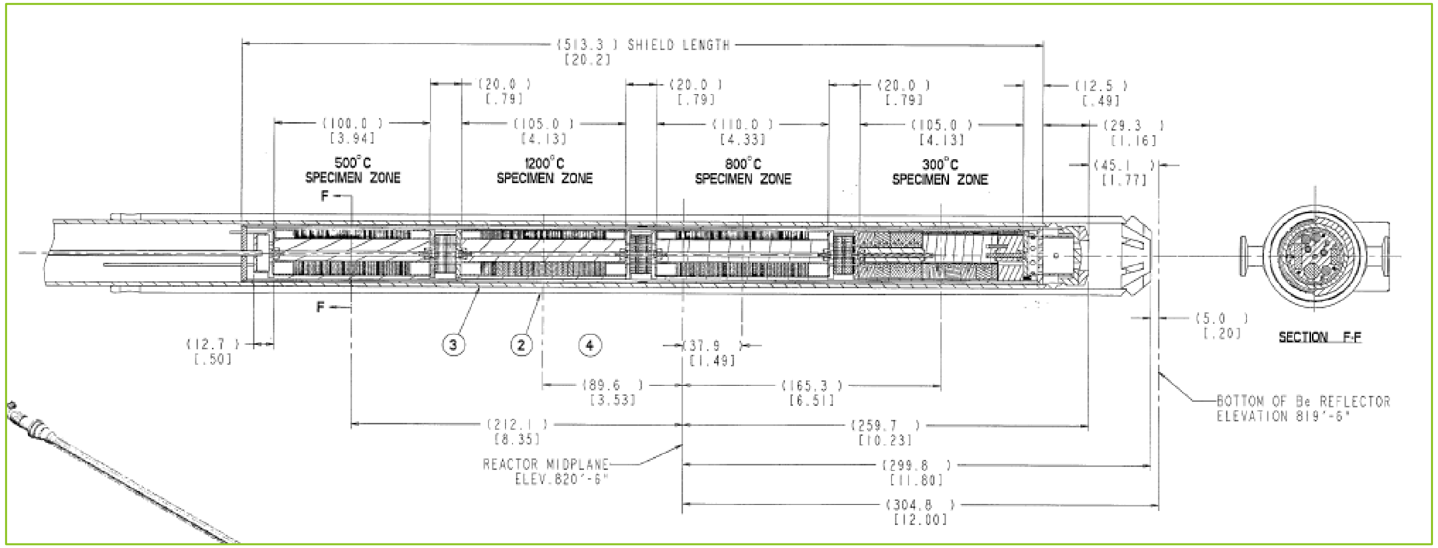
HFR (Petten)



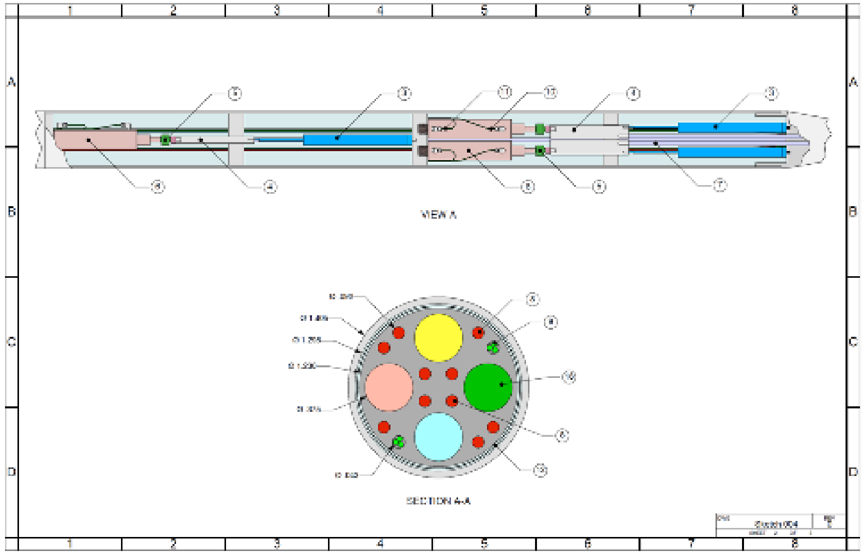
- ***1-2 flux target position***
- *60cm (24inch) height*
- *17 experimental positions*
- *Rabbit*

Vender Irradiation Capsules

ORNL (HFIR)

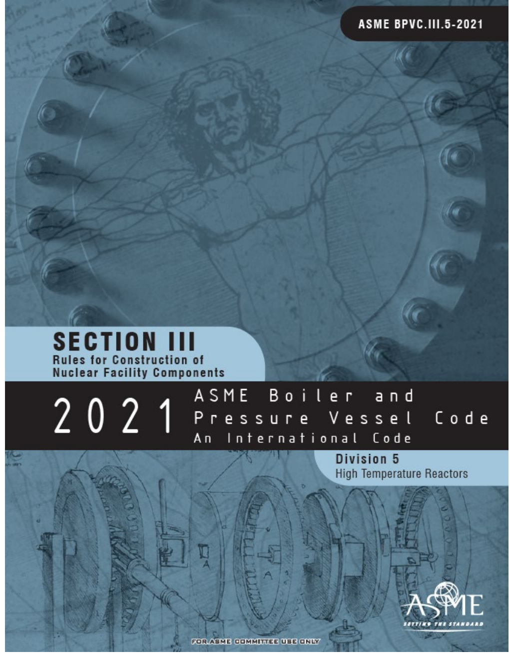


INL (ATR)



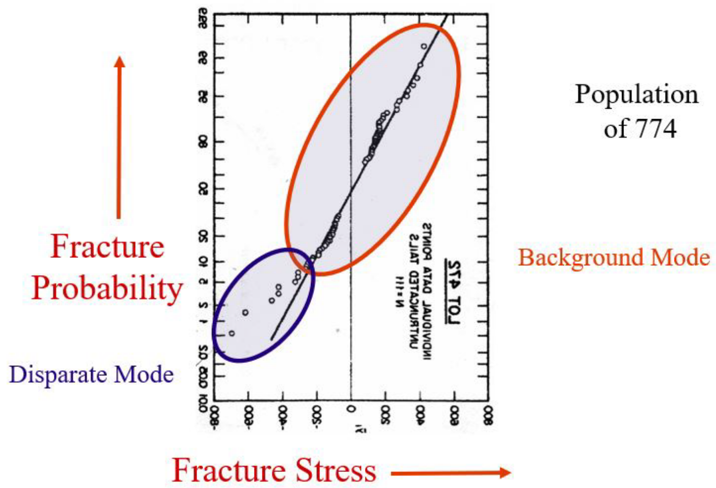
- DOE recognizes that there is still a need for graphite irradiation experiments
  - Preparing "generic" capsule designs at INL (ATR) and ORNL (HFIR)
- Vendors can then come in and modify the generic design to their specific requirements
  - Temperature, mechanical load (creep), dose, etc.

Design and construction rules (ASME-based)



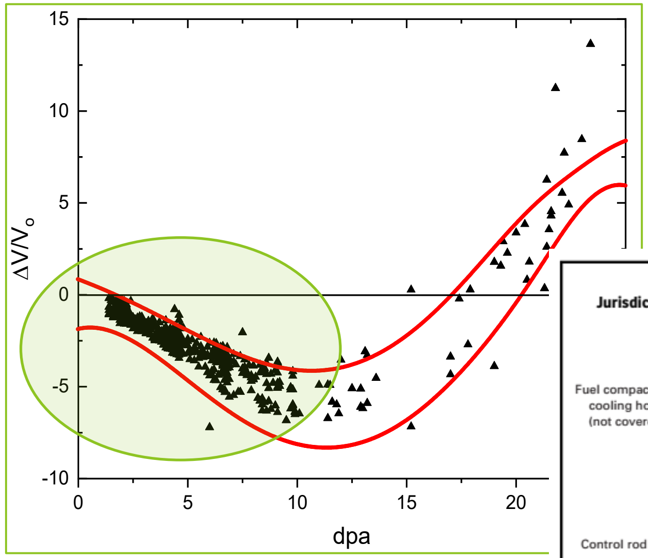
- Focus has been on component and core design (HHA-3000)
  - Significant progress has been made in last 2-3 years
  - We really know the Design code now
- Several sensitivity studies to understand ramifications to code rule changes

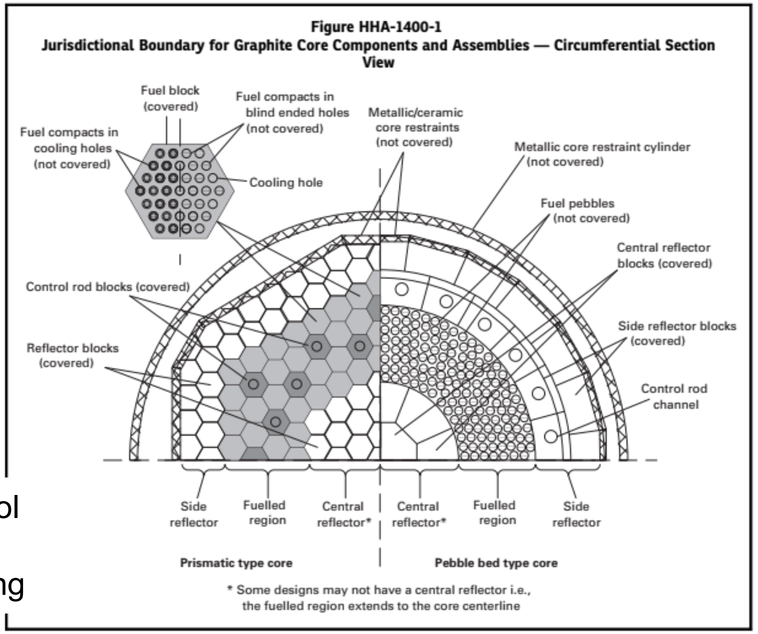
◆ US experiments, H451 (Kennedy and Eatherly, 1986)

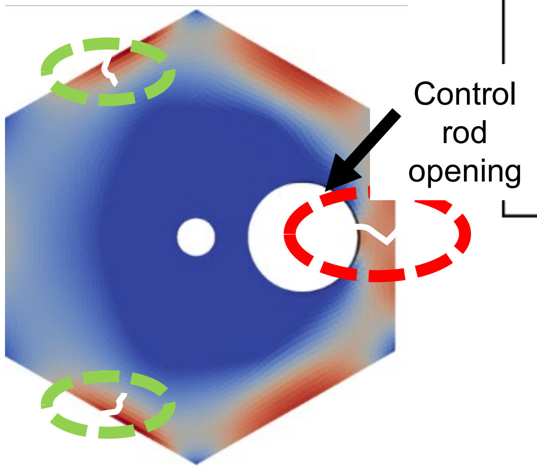


Record Title	Record Number	Project Manager	Status
Modify notation and definitions	R20-1308	Andrea Mack (INL)	Approved
Update shape parameter in the full assessment	**R21-1581**	**Andrea Mack (INL)**	**In-process**
Correct notation and equations in HHA-II-3200	R23-170	Andrea Mack (INL)	Approved
Stress terminology in the simplified assessment	R23-473	Pierre-Alexandre Juan (Kairos Power)	In-process
Full assessment flow chart	R23-1349	Gwennael Beirnaert	Approved
Modify Vm	R23-2066	Michael Saitta (MPR)	In-process
Assessment interpretations: POF vs. POCI	**R24-432**	**Andrea Mack (INL)**	**In-process**

Design and construction rules – What's next?







- Beginning to address degradation
  - Design, Materials, Historical Data, etc.
- Component failure
  - Component failure definition
    - ***Intn'l effort (IAEA)***
  - How & where it should be addressed in code
- Operation (Section XI)
  - RIM
  - Inspections
  - Degradation

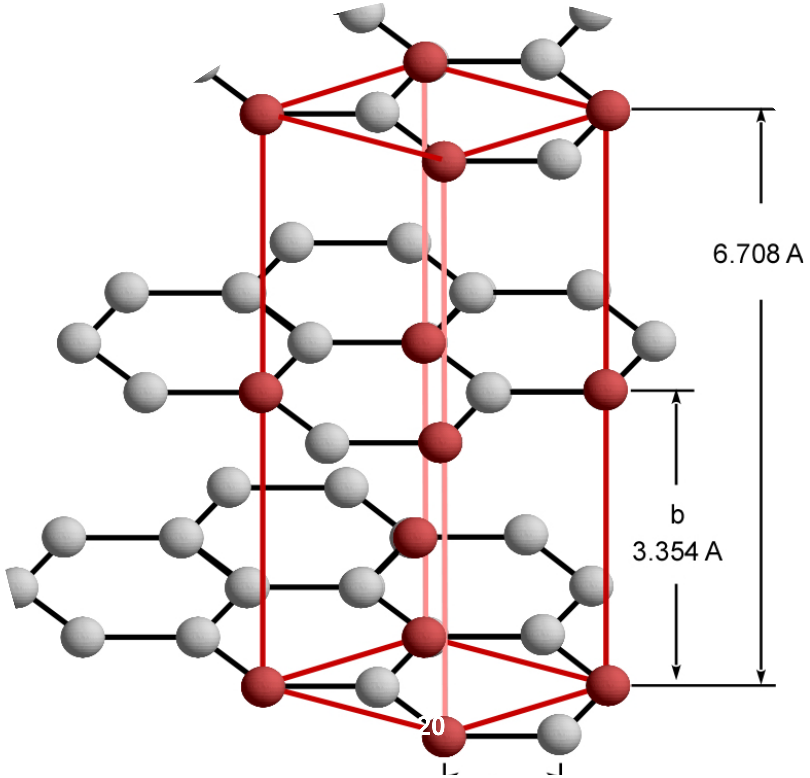
Additional areas just getting off the ground

- **Waste**
  - DOE's IRP : 3-4 year project to help USA get back up to speed
    - **An assessment of USA regulations and what we need to do in future**

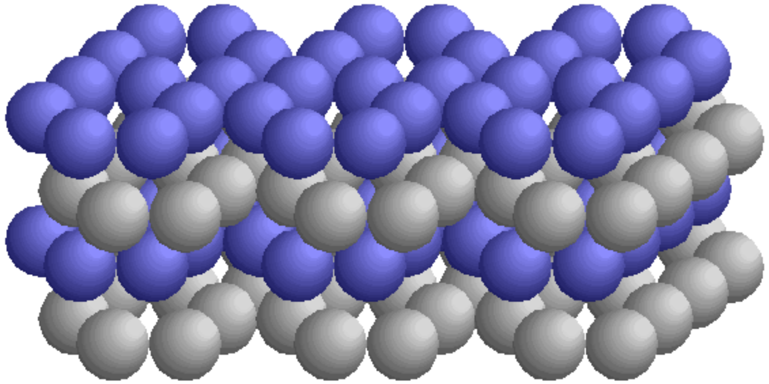
- **Component Failure (definition)**
  - It's been recognized that we need to understand and define a generic definition for graphite component failure
  - This would help the problems many designers are facing for operation
    - ***How, why, and what to expect when inspecting***
  - Working with IAEA to begin a Coordinated Research Project (CRP)
    - ***Several countries willing to contribute expertise***

We need to be <u>serious</u> about <u>Nuclear Graphite</u>

- Look, there is no ***Nuclear Graphite*** grade(s)
  - We pick up and use what other industries have developed
    - ***Other than isotropy research (i.e., Gilsocarbon grade), little "nuclear" manufacturing goes into making graphite for nuclear components (other than purification)***
  - Case in point: Today we use Semi-conductor grades for nuclear applications
  - **Why?** It's not particularly irradiation resistant.
    - Or oxidation resistant.
      - Or molten salt resistant
- We need to begin manufacturing nuclear graphite grade(s)
  - High irradiation stability, low oxidation rates, chemically resistant, high fracture resistance, other properties of interest to nuclear applications



How do we make “Nuclear” graphite



- We need to understand underlying degradation mechanisms
  - Need to better understand **accommodating porosity**
    - ***Mesoscale dimensional change is critical***
  - Need to develop better (different) coatings/additives for oxidation
  - Need to better understand the irradiation property changes
  - Much better understanding of the microstructures formed

- Graphite manufacturers, reactor developers, and researchers need to work together
  - It’s not just thermal conductivity, CTE, and strength improvements.
  - The unique microstructures which produce irradiation accommodating porosity need to be discovered.
  - And yeah, I know. No one wants to give up an economic advantage
    - ***But the first ones to develop grades with turnaround doses 2X, 3X, or 4X higher will be the preferred grades.***

GAS-COOLED
REACTOR

ADVANCED REACTOR
TECHNOLOGIES PROGRAM

Thank You

William Windes

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