INL/MIS-23-73774-Revision-0

ASME Irradiation Model

July 2023

Changing the World's Energy Future

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Idaho National Laboratory

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ASME Irradiation Model

How to deal with irradiation data in ASME code rules

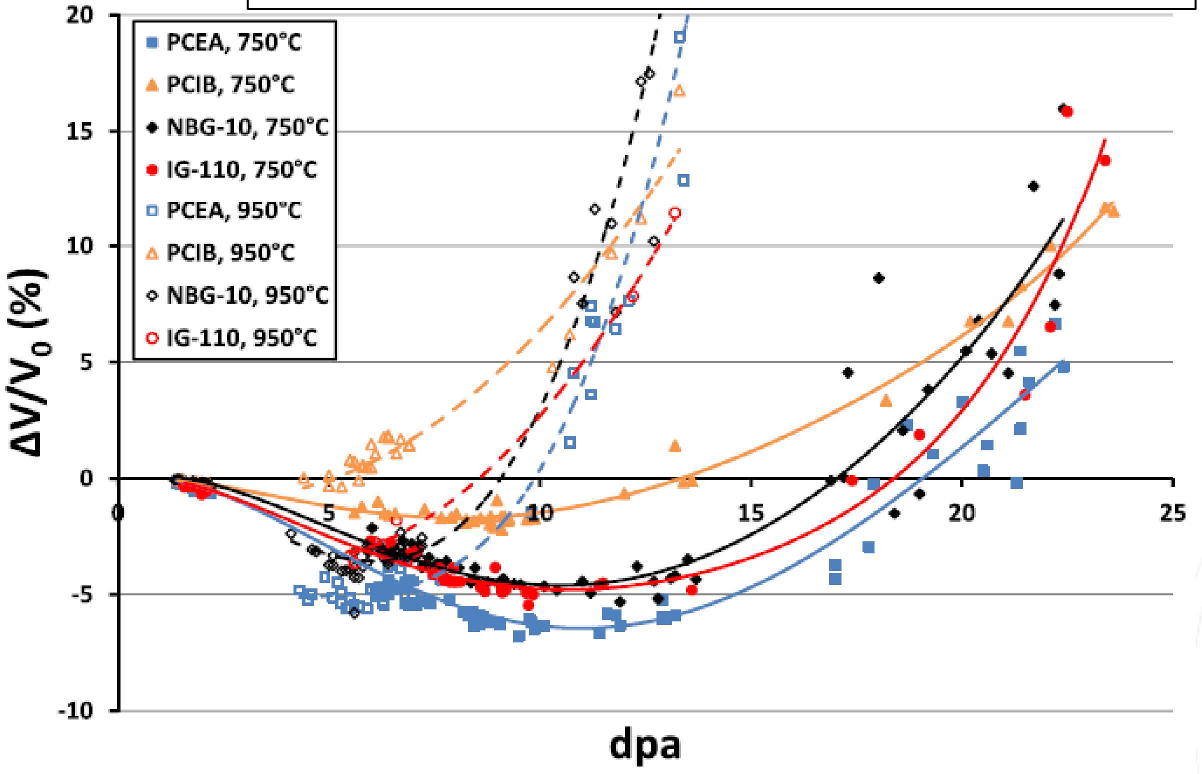
DOE ART Gas-Cooled Reactor (GCR) Review Meeting
Virtual Meeting
July 25 – 27, 2023

ART
Advanced Reactor Technologies

Nuclear graphite has a significant challenge (problem)

- There is not enough irradiation data to qualify graphite for nuclear application
  - For all grades
  - At all irradiation temperatures
  - Over entire range of anticipated dose
- Problem is the variety of different grades
  - No single “nuclear” grade
  - Historical grades with irradiation experience no longer available
  - Irradiation data across available temperature range is limited
- We don’t have time/room in available MTRs to get all the required data

M.C.R. Heijna et al. / Journal of Nuclear Materials 492 (2017) 148-156



ARTICLE HHA-II-2000 MATERIALS DATA SHEET - ASME BPVC.III.5-2021

- ASME code rule modification for support of new reactor concepts and commercial vendors.
- Irradiation induced property change.
  - Key properties include, but is not limited to, the strength, elastic modulus, coefficient of thermal expansion, **dimensional change**, etc.
- The turnaround dose signals when many other properties will significantly deteriorate

ASME MDS Sheet for qualification of HTR graphite for NRC licensing.

Irradiated Graphite

Property	Units	WG	AG
Dimensional change [.] (31)	______	______	______
Creep coefficient [.] (32)	______	______	______
Coefficient of thermal expansion [.] (33)	______	______	______
Strength [.] (34)	______	______	______
Elastic modulus [.] (35)	______	______	______
Thermal conductivity [.] (36)	______	______	______

GENERAL NOTES:
(a) WG, AG refers to the with- and against-grain direction of the material.
(b) [.] indicates a dimensionless quantity.

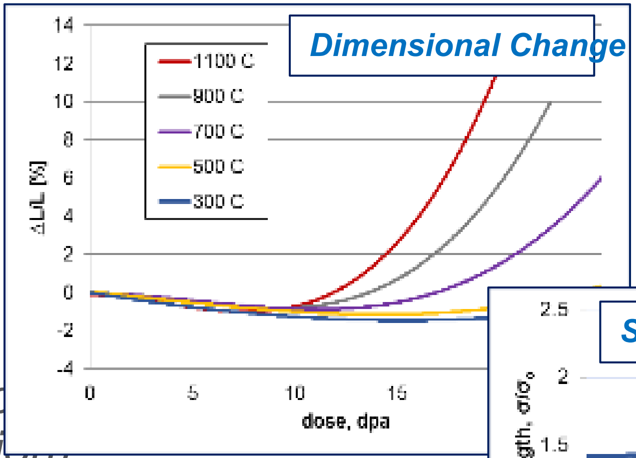
NOTE:
(1) If the maximum intended use temperature exceeds 1,832°F, then the temperature dependent data shall be extended to cover the property values at the maximum intended use temperature.

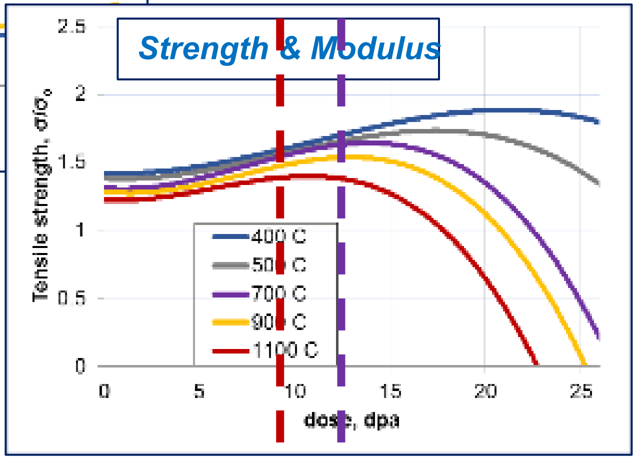
(07/21)

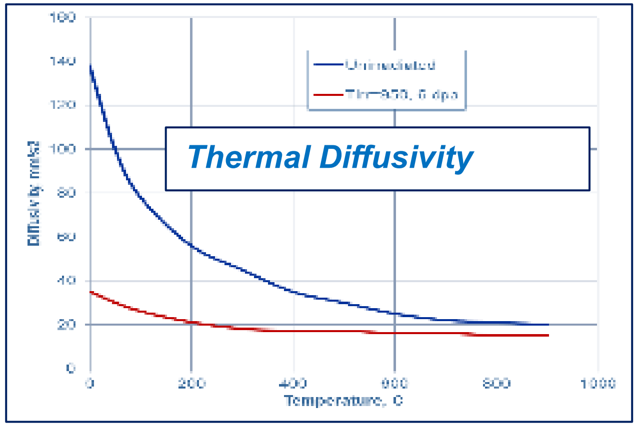
Irradiation Behavior

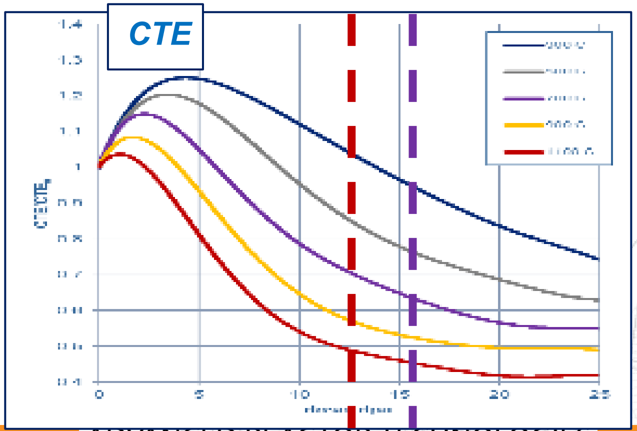
Significant changes occur during normal operation:

- Density - Densification
  - *Graphite gets denser with irradiation until Turnaround do*
  - *After Turnaround density decreases (volumetric expansion)*
  - *Formation of microcracks (molten salt consideration)*
- Dimensional change
  - *Turnaround dose is key parameter*
  - *Highly temperature dependent*
- Strength and modulus
  - *Graphite gets stronger with irradiation …*
  - *Until Turnaround. It then decreases*
- Coefficient of thermal expansion
  - *Initial increase but then reduces before Turnaround*
  - *CTE is why properties are so temperature dependent*
- Thermal conductivity
  - *Decreases almost immediately to ~30% of unirradiated values*
  - *At temperatures it is same as unirradiated conductivity*

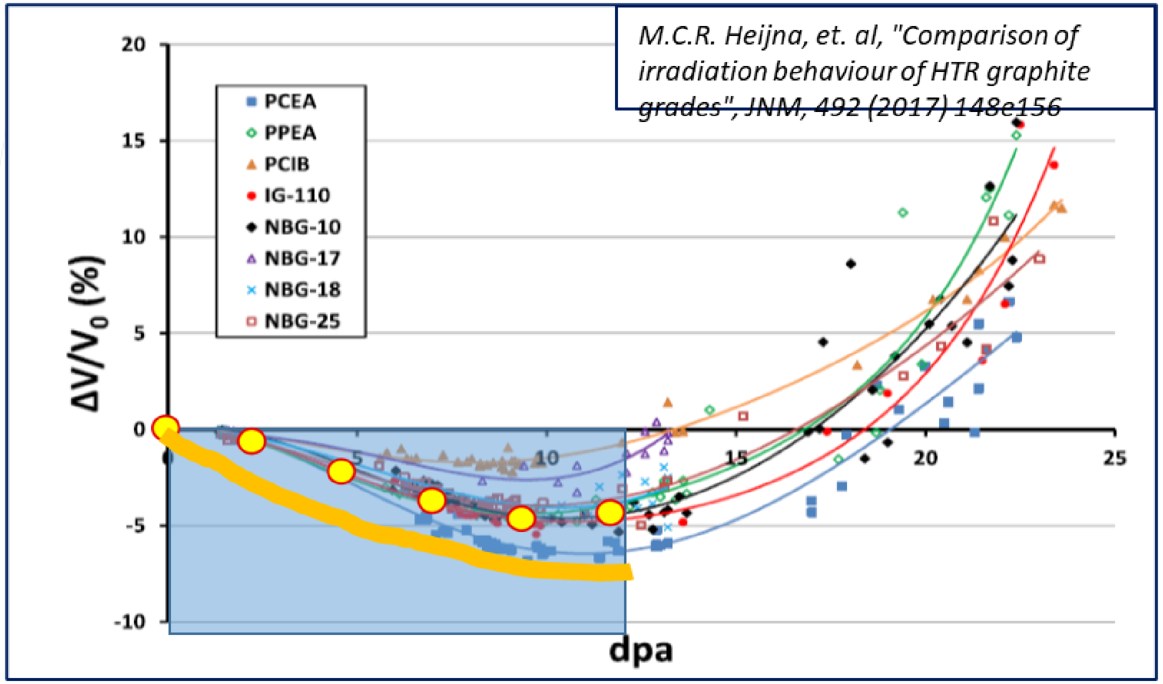








Leveraging the data generated by GIF countries last 20 years



So long as "new" data falls within data cloud we can use all grades to predict behavior

- AGC Experiment = 20+ years
- We need figure out a way to get needed irradiation data without new "AGC" tests
- Why not leverage all existing data?
  - ***Assume all grades behave similarly***
  - At least until turnaround dose is achieved
- If we can demonstrate that all graphites behave similarly we can create engineered limits
- ***Let's see if we can do this …***

Dimensional Change Theory

$$\frac{dG_x}{d\gamma} = A_x\left(\frac{1}{X_c}\frac{dX_c}{d\gamma}\right) + (1 - A_x)\left(\frac{1}{X_a}\frac{dX_a}{d\gamma}\right) + f_x$$

x: Direction (not specific)

γ: Fast neutron fluence (n/m^2)

A_x : Structural factor: ration of grains to *c*-axis within x direction (i.e., purely isotropic $A_x = 0.5$)

X_a, X_c : Fractional dimensional change to *a*- and *c*- axes

f_x: Fractional dimensional change from pores per neutron fluence

Integration yields: $\boldsymbol{G_x(\gamma) = A_x G_c(\gamma) + (1 - A_x) G_a(\gamma) + F_x(\gamma)}$

Linear

Non-linear

J. E. Brocklehurst, B. T. Kelly, Carbon, 31, 155–178 (1993).

All Graphites Behave Similar – Can we Predict the %Δ?

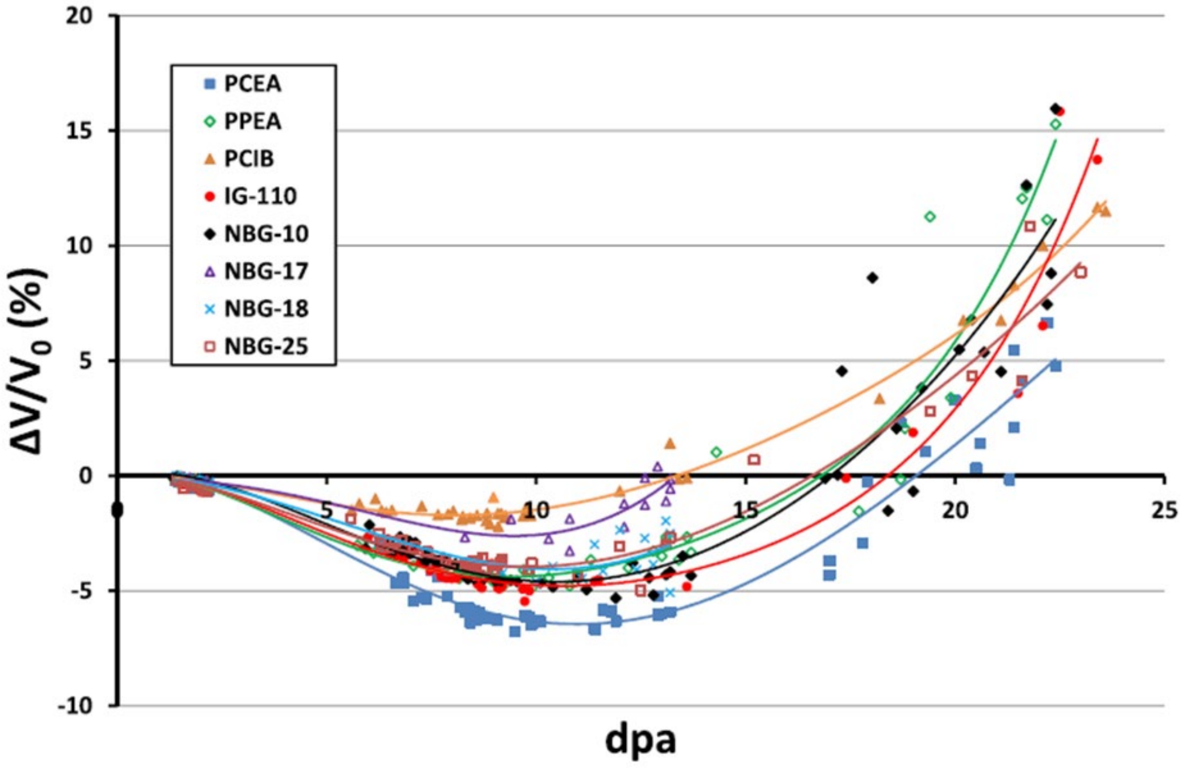


Fig. 2. Dimensional change as function of dpa at 750 °C.

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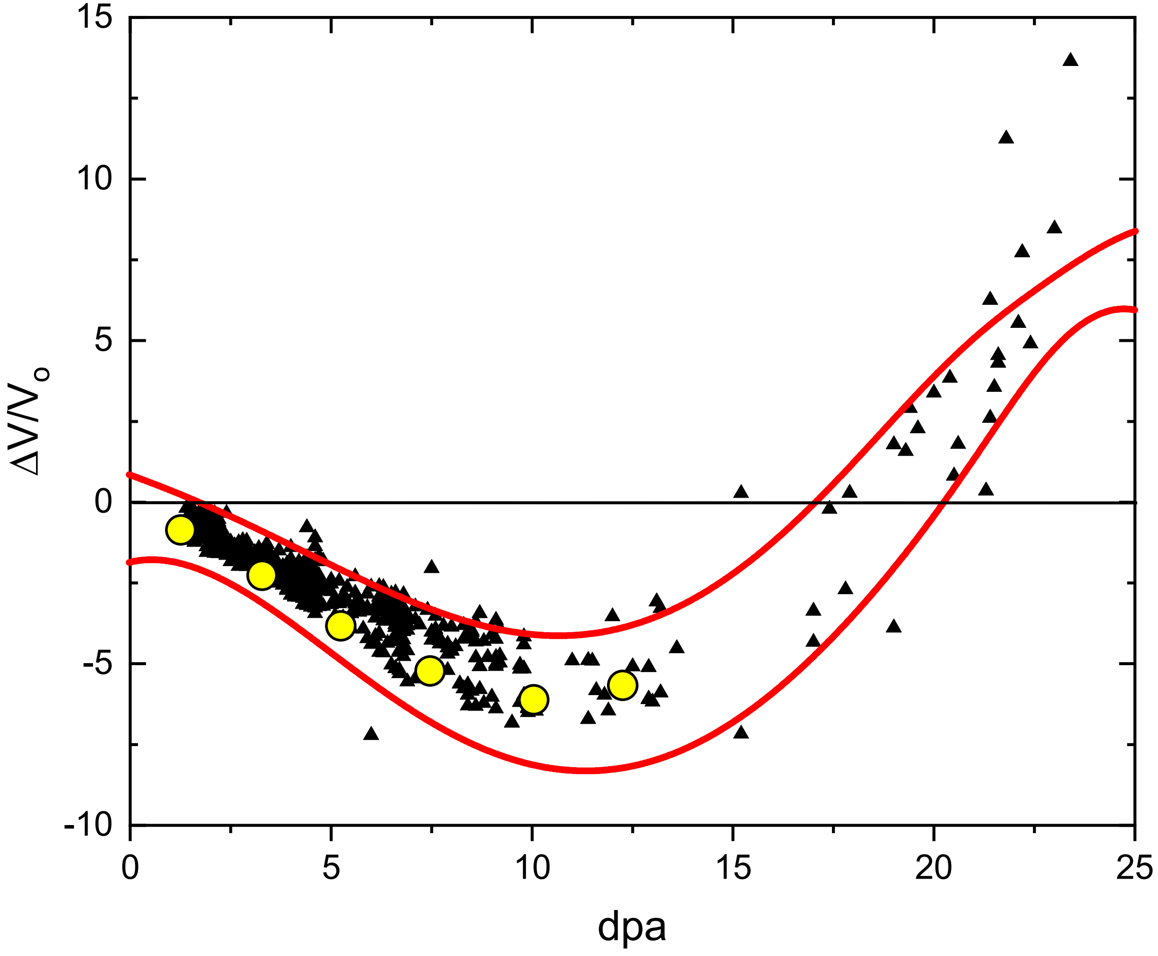
- Proposed is empirical polynomial fitting *up to* turnaround.
- To be used as a reference for ASME code / commercial vendors, for dimension change (%Δ) at a given dose.
- Shown is 5th order polynomial fits, which accurately captures the delayed dimensional change response.
- Literature reviews suggest PCEA to have the largest dimensional change of candidate grades.
- Can PCEA data be used as a 'lower bound' for all candidate grades in the design code (% dimensional change).

Irradiation Data From AGC1-3 and InnoGraph



- Nuclear graphite grades:
  - NBG-10, NBG-17, NBG-18, NBG-25, PCEA, H-451, IG-110, and 2114.
- ***Needs*** to be refined by temperature.
- For adequate fitting, irradiation data was taken from **400-800°C**.
  - Currently collaborating with ORNL to compile and produce open-source data for analysis.
- With enough data, additional refinements may be possible.
  - Example. by small, medium and large grained graphites.

Turnaround Dose is a Function of Temperature

- Identify turnaround dose (TAD) as a **function of temperature**.
- Turnaround is a temperature dependent response (thermally activated).
- Define an Arrhenius function

$$\mathbf{TAD}(\boldsymbol{T}) = \boldsymbol{A}\ \boldsymbol{exp}\left(\frac{-\boldsymbol{E_a}}{\boldsymbol{k_b T}}\right)$$

- Fundamentally, on the atomic scale, all nuclear graphites are the same. sp_2 bonded Carbon with some degree of disorder.
- Variation in the irradiation response amongst grades comes from differences in the meso – macroscale features.

Assume all grades have similar defects.

Thus, same activation energy (E_a).

All other graphite differences are in ***A***

$$\boldsymbol{A} \propto (\boldsymbol{grain\ size}, \rho_{\boldsymbol{o}}, \boldsymbol{CTE})$$

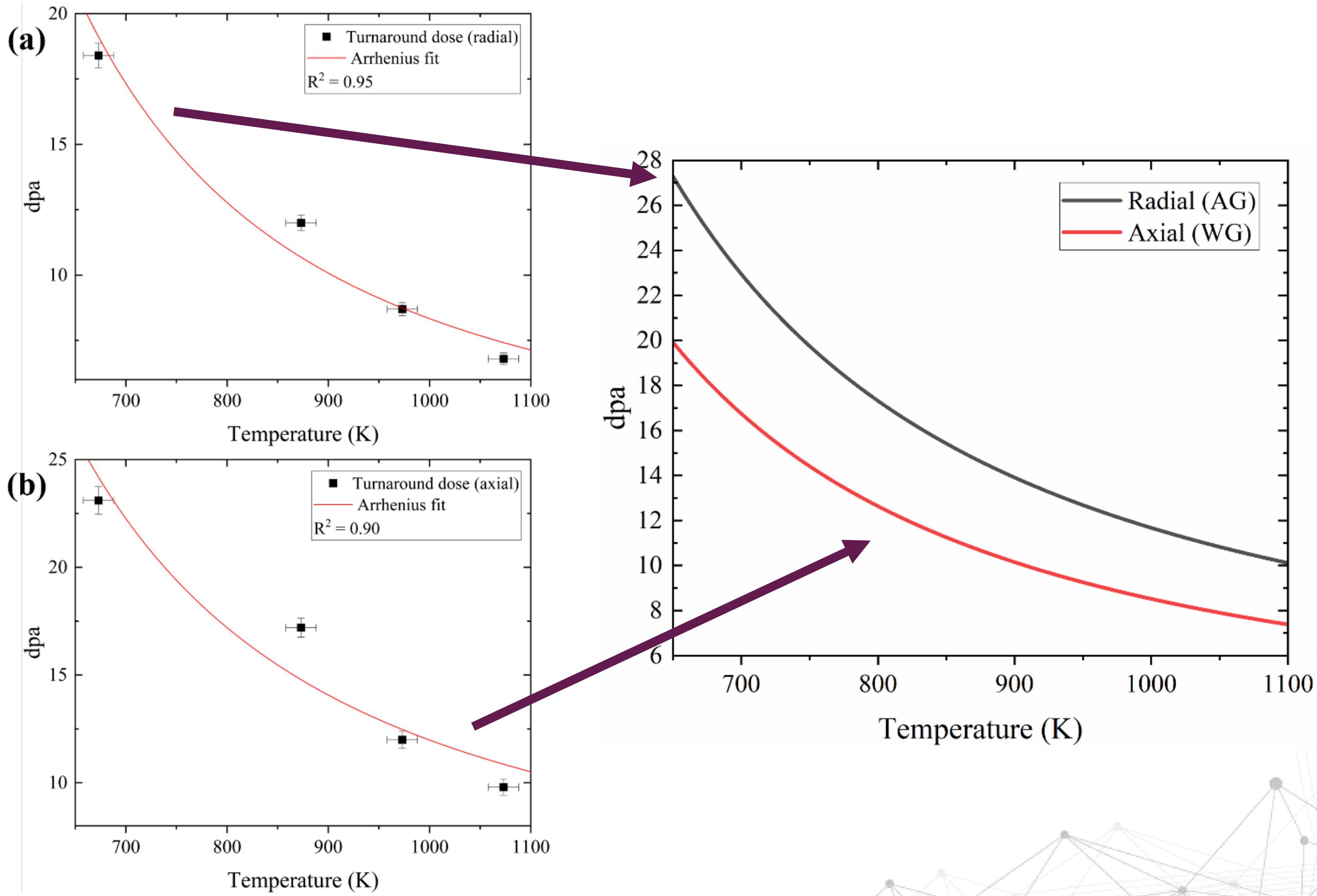
DOE-HTGR-88111, Graphite Design Handbook, General Atomics Company, CA, 1988

Arrhenius Fits for H-451 Dimensional Change Data

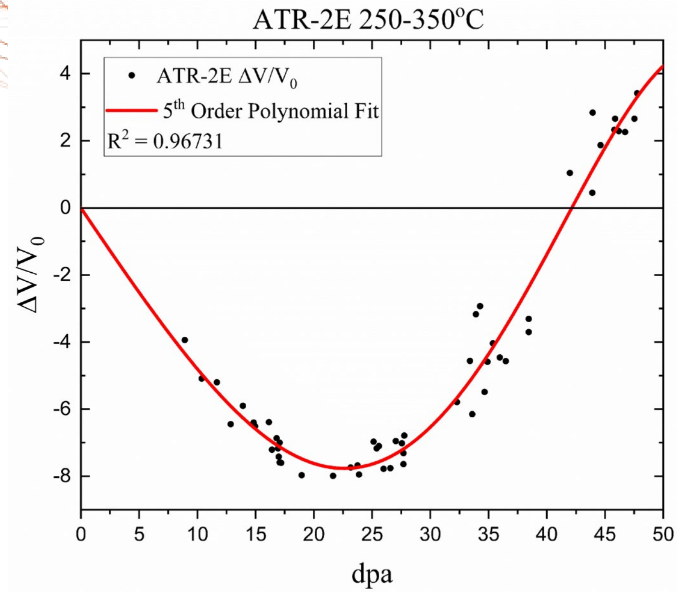
$$\mathbf{TAD}(T) = A\, exp\left(\frac{-E_a}{k_b T}\right)$$

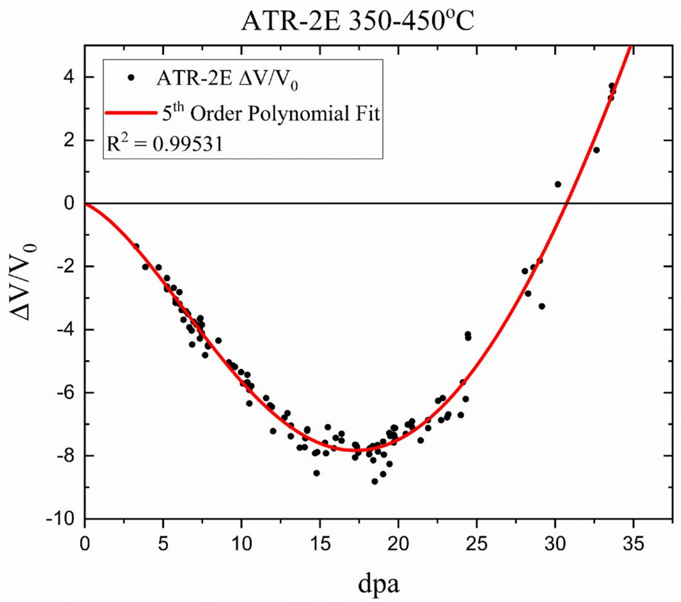
- During the first fitting, the activation energy and pre-exponential were allowed to vary.

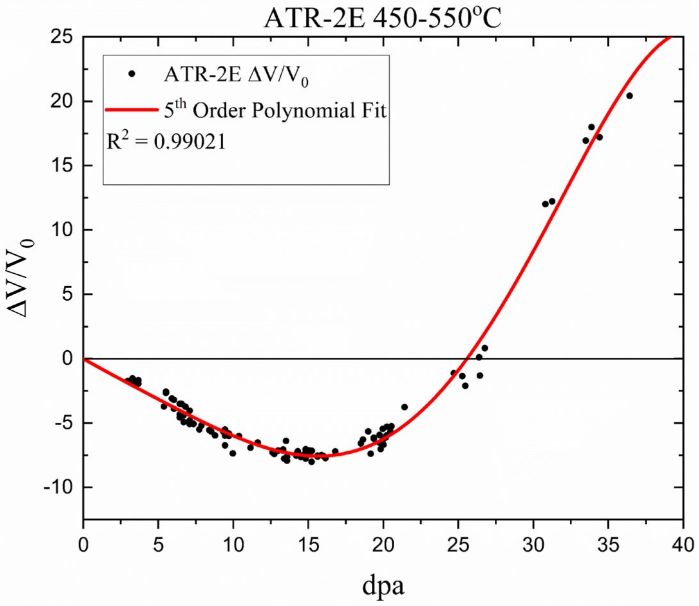
- A second fitting was conducted by setting the activation energy as an average from axial and radial data.

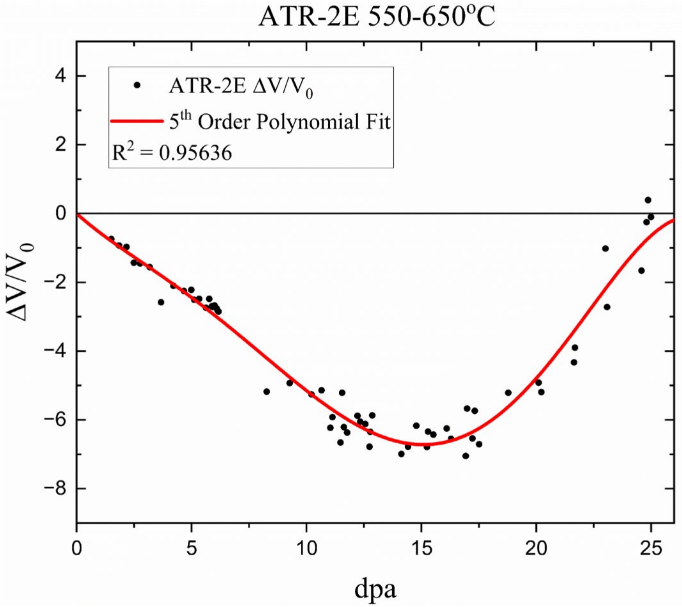


TAD Extrapolated with 5th Order Polynomial





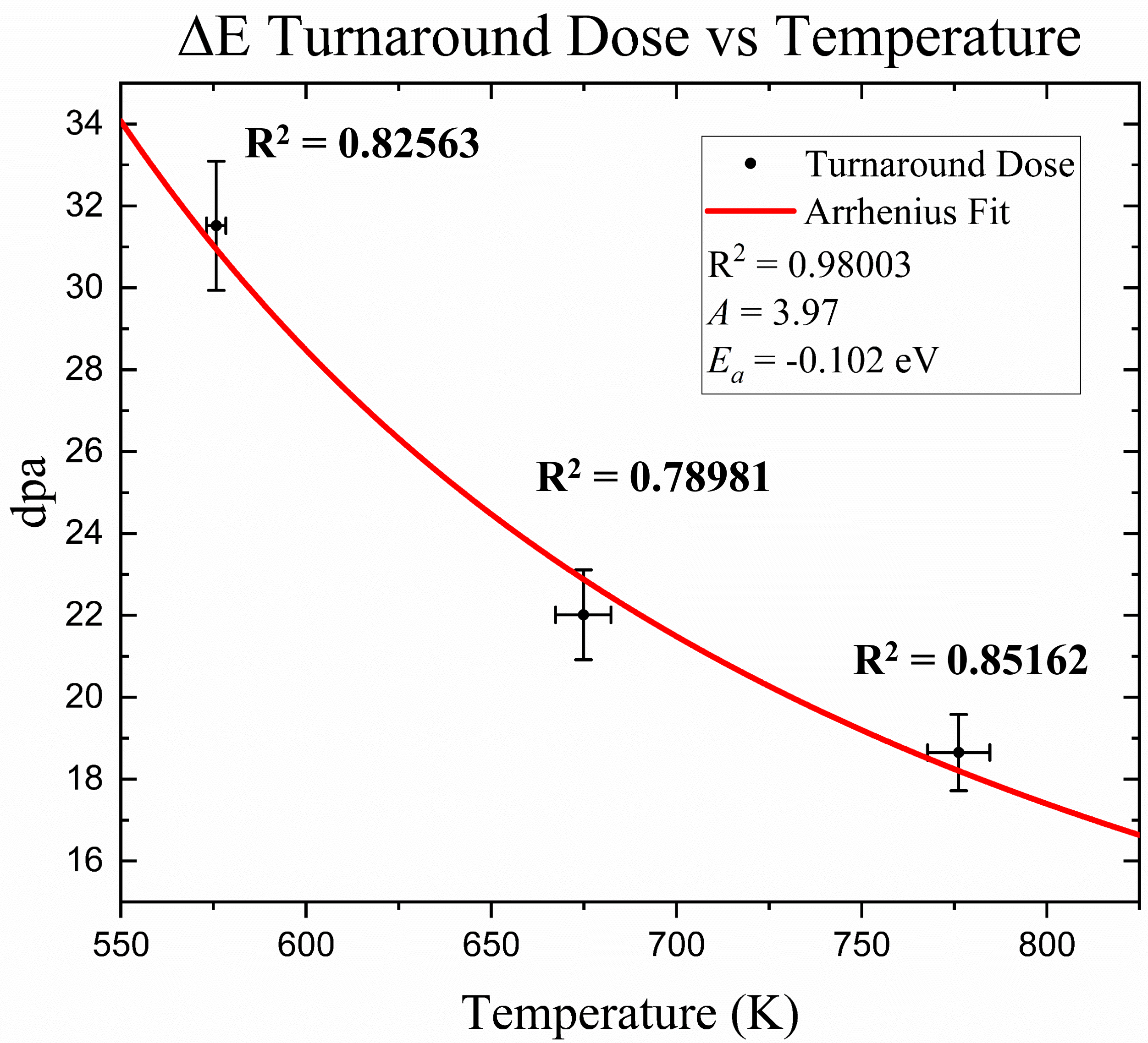




Irradiation temperature is critical

- “Same” activation energy implies “same” defects
  - ***Defects form at different temperatures***
  - ***Defects can anneal out at higher temperatures***

$$\mathbf{TAD}(T) = A\, exp\left(\frac{-E_a}{k_b T}\right)$$



- The R^2 value for the Arrhenius plots is misleading.
- The 'goodness' of fit cannot be greater than the data from which it came from.
- Looking to add more data from AGC and INNOgraph
- Working to improve empirical irradiation data (weighted)

Conclusions

- An Arrhenius approach to predict the turnaround behavior may be a viable solution for the ASME MDS requirements for all nuclear graphites.

- This model is anticipated to include the elastic modulus and electrical resistivity.

- A draft manuscript to be submitted to a referred journal is anticipated by the end of FY23.