

Self-alpha irradiation of $\text{UO}_2\text{-UB}_2$ fuel

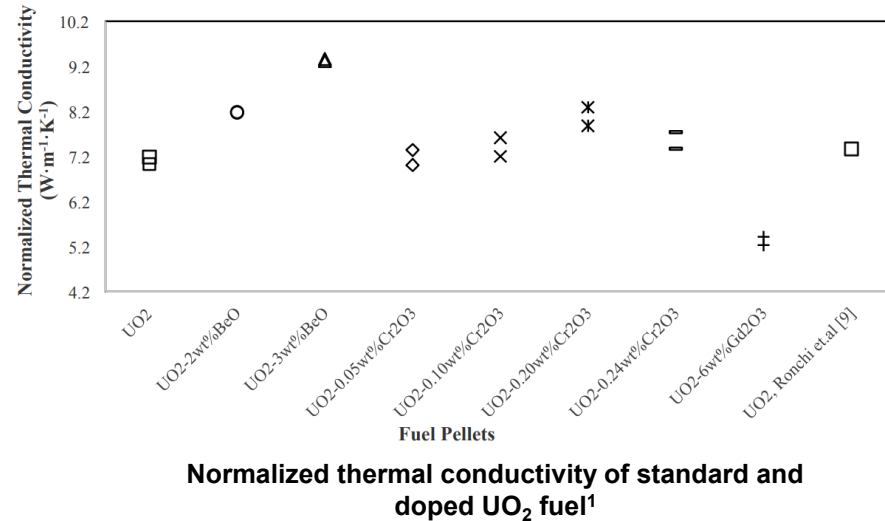
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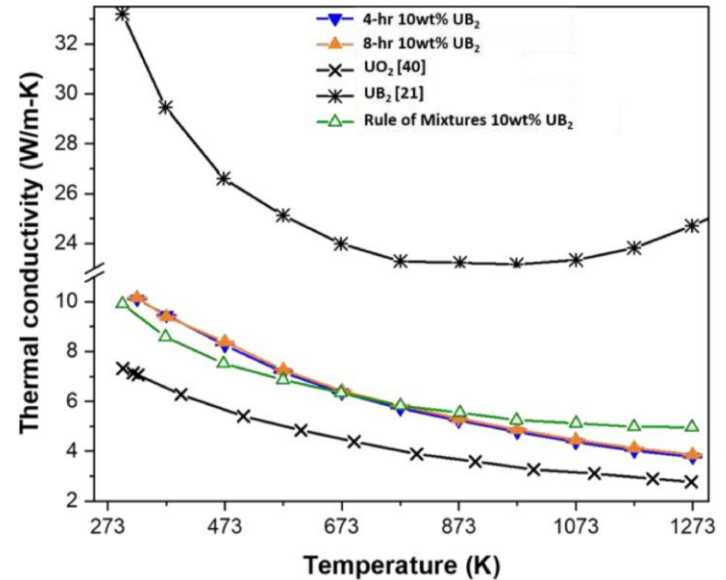
- UO_2 has been the primary fuel used in LWRs for a long time.
- But low thermal conductivity (TC) & lower U density of this fuel have always posed concerns.
- Non-fissile additives (BeO , Cr_2O_3 , Gd_2O_3 etc.) have been/are being researched to increase TC of UO_2 ^{1,2}.
- But following this path decreases U density even further.
- Several groups have started to investigate fissile additives.



¹Camarano et al., INAC 2021

²Arborelius et al., J. Nucl. Sci. Tech 2006

- UB_2 is one of the promising additives due to it's:
 - Higher TC (25 W/mK ~ 7 W/mK of UO_2)
 - Favorable corrosion resistance
- A composite fuel like UO_2 - UB_2 will have higher U density, higher TC and corrosion resistance than UO_2 .



Measured TC vs temperature for UO_2 , UB_2 and UO_2 -10wt% UB_2 ³

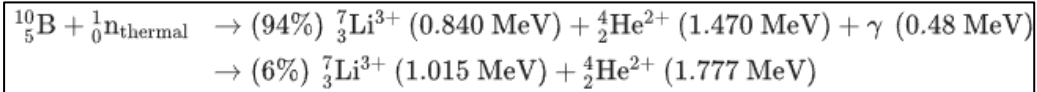
Naturally Available Boron

80.1% ¹¹B

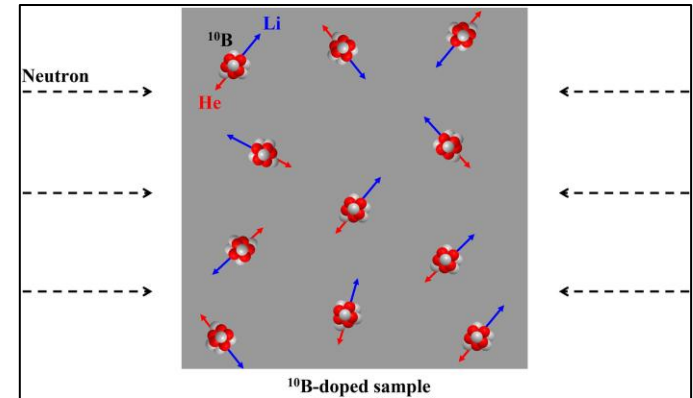
0.0055 b

19.9% ¹⁰B

3841 b

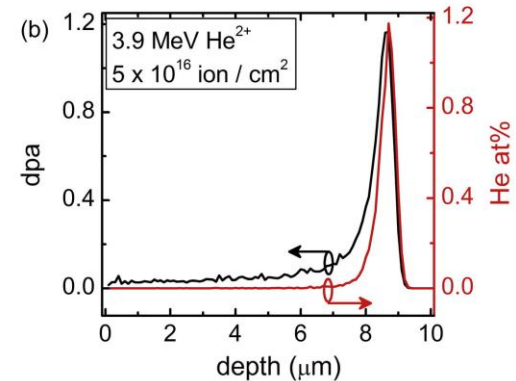
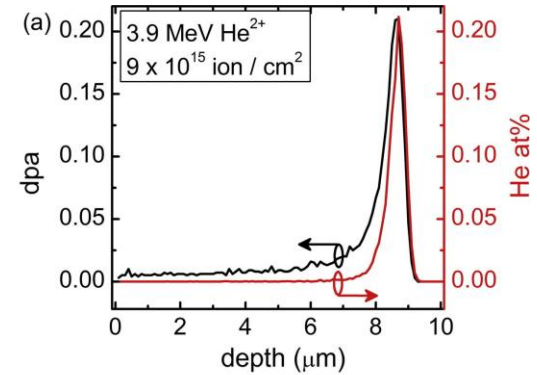


- The ¹⁰B(n, α)⁷Li reactions can emit MeV-scale Li and He ions, which create homogeneous radiation damage and He implantation in boron-containing material⁴.
- ¹⁰B doping has been employed in steels to study⁴⁻⁷:
 - He embrittlement
 - Void swelling
 - Alteration in mechanical properties due to He implantation
 - Fusion-relevant radiation condition (high He appm-dpa)
- **Boron may similarly act as an internal alpha source in the boron-containing nuclear fuels.**



Schematic illustration of ¹⁰B doping methodology to simulate helium production and dpa accumulation⁴

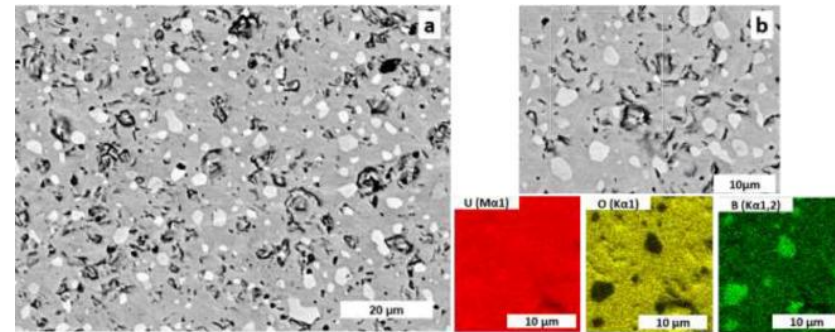
- 3.9 MeV He ion irradiation produces an approx. 9 μm damage profile in UO_2 with:
 - A plateau region within 0 – 8 μm
 - A high damaged region within 8 – 9 μm
- In contrast, the $^{10}\text{B}(n, \alpha)^7\text{Li}$ may generate high-energy He ions internally within boron-containing materials, leading to more spatially distributed helium implantation and displacement damage.



SRIM damage profile for 3.9 MeV He^{2+} irradiated UO_2 ⁵

- To demonstrate self-alpha irradiation induced homogeneous displacement damage and He implantation in a $\text{UO}_2\text{-UB}_2$ multiphase fuel.
- To characterize the radiation/annealing induced extended defects (dislocations and He bubbles) in both UB_2 and UO_2 .

- In this study, we focus on a UO_2 -10%wt UB_2 composite fuel (80.1% ^{11}B and 19.9% ^{10}B in UB_2).
- Were prepared by pressure-less sintering at 2073 K in an argon atmosphere.
- Bi-modal average particle size of 7-20 μm and approximately 2 μm for the UO_2 and UB_2 , respectively.



SEM-EDS of the UO_2 - UB_2 sample used in this work³

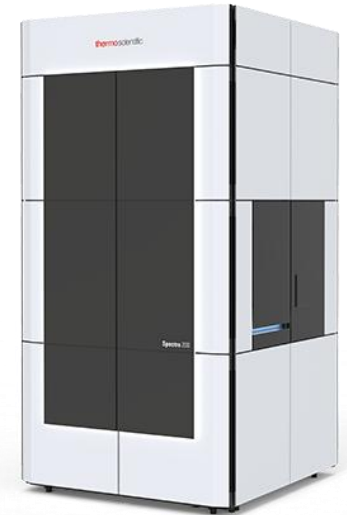
- NC State's PULSTAR was used to irradiate the 3 pieces of sample for 31.2 hours at full exposure.
 - Fast (1 MeV) and thermal neutron fluxes of 3.99×10^{11} and 1.74×10^{12} n.cm⁻².s⁻¹, respectively.
 - dpa by fast neutron flux: **3.81×10^{-5} dpa**
dpa by $^{10}\text{B}(n, \alpha)^7\text{Li}$: **0.005 dpa**

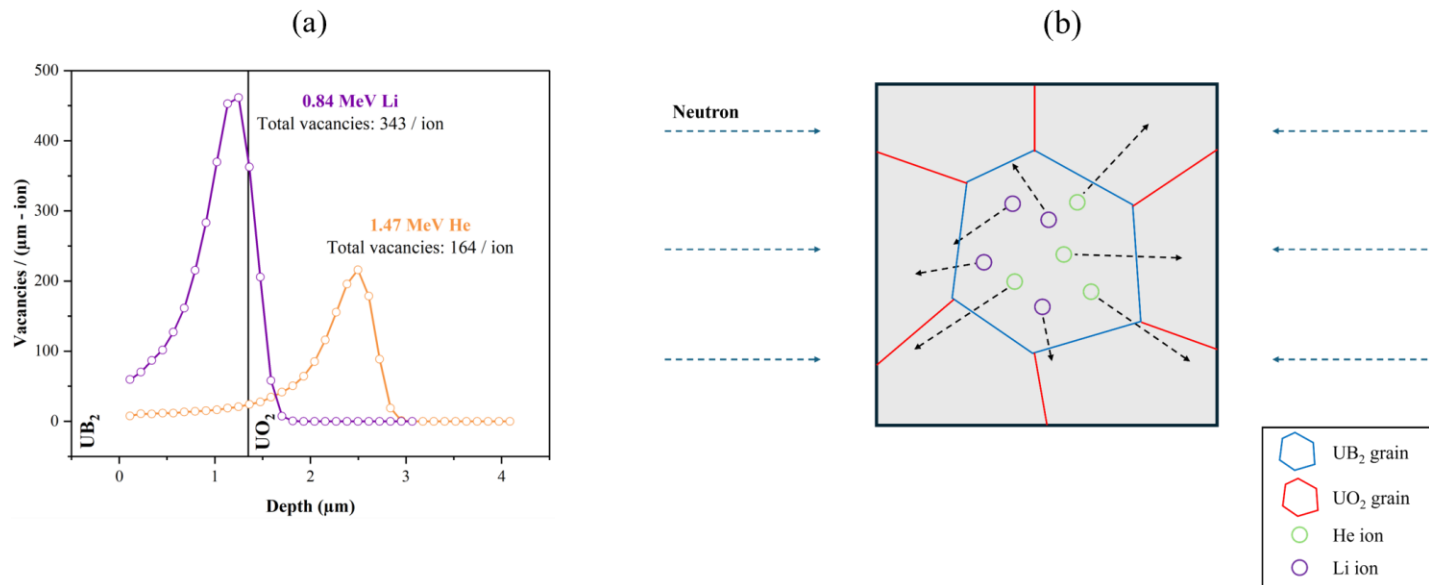
Material	Code	Annealing Condition Post-Irradiation
UO ₂ -UB ₂	1932-3	500C 1hr
	1932-1-a	As irradiated – No annealing
	1932-1-b	500C 1hr – 1000C 1hr



- PALS was conducted before and after irradiation (1932-3 and 1932-1-a) to estimate the formation of defects.

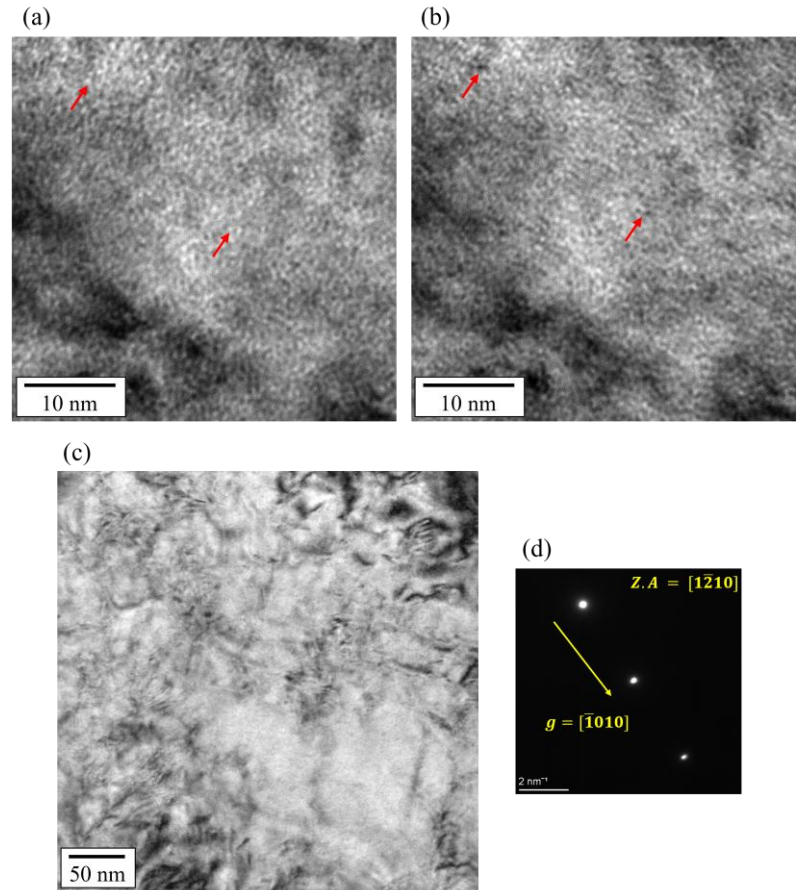
- The samples were then sent to CMESIC on Sep 15, 2025 for PIE.
- Quanta FIB was used to prepare TEM lamellas.
- Spectra 300 was used to characterize extended defects formed within both UO_2 and UB_2 grains.

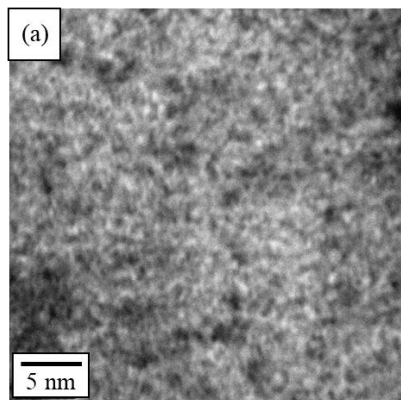




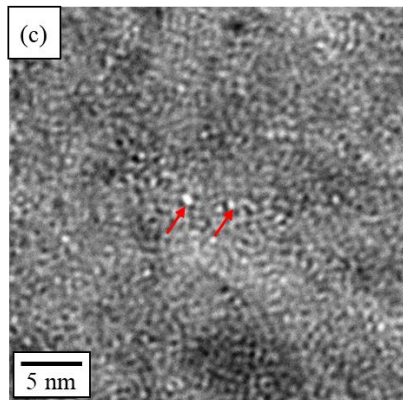
**Total number of vacancies/ion in $\text{UO}_2\text{-UB}_2$ due to He/Li ions produced by self-alpha irradiation (a)
Schematic diagram to illustrate self-alpha irradiation's effect on $\text{UO}_2\text{-UB}_2$ fuel (b).**

- Subnanometric He ion induced bubbles were observed in UB_2 phase.
- BF-TEM image acquired with $\vec{g} = [\bar{1}010]$ excited near $[1\bar{2}10]$ zone to visualize $\langle a \rangle$ type dislocation loops forming on the prismatic planes.
- At the relatively low dose considered here, dislocation loop formation was not expected and the observation agrees with this.

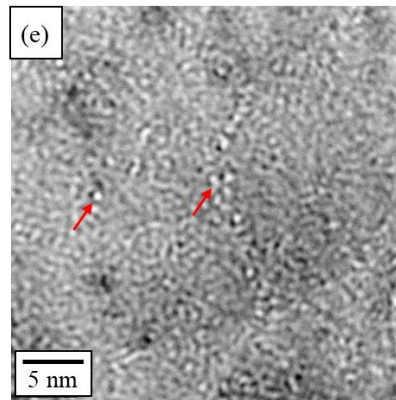




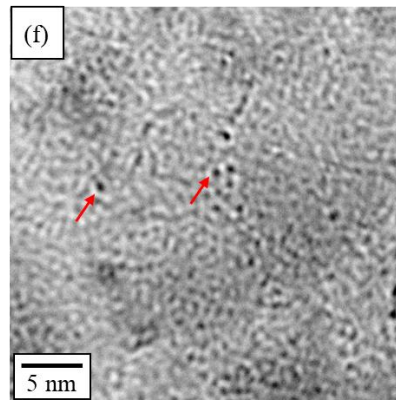
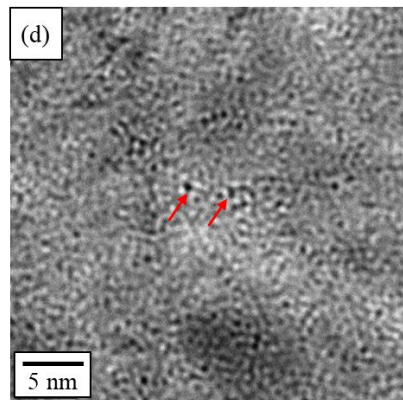
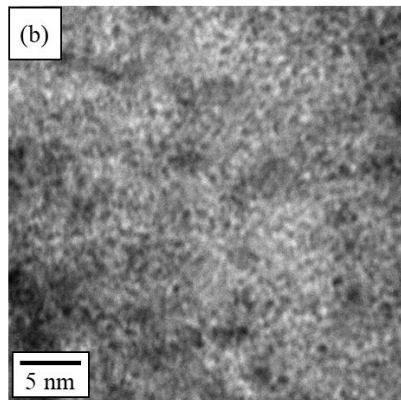
As-irr.



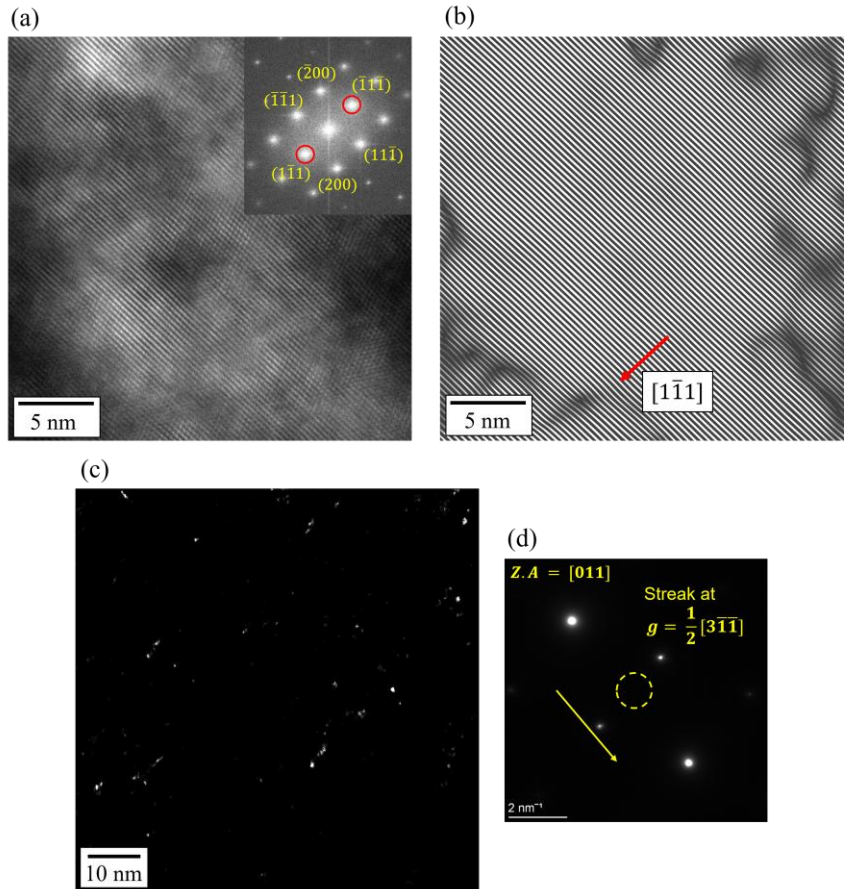
As-irr. + 500°C



As-irr. + 500°C 1hr + 1000°C 1hr

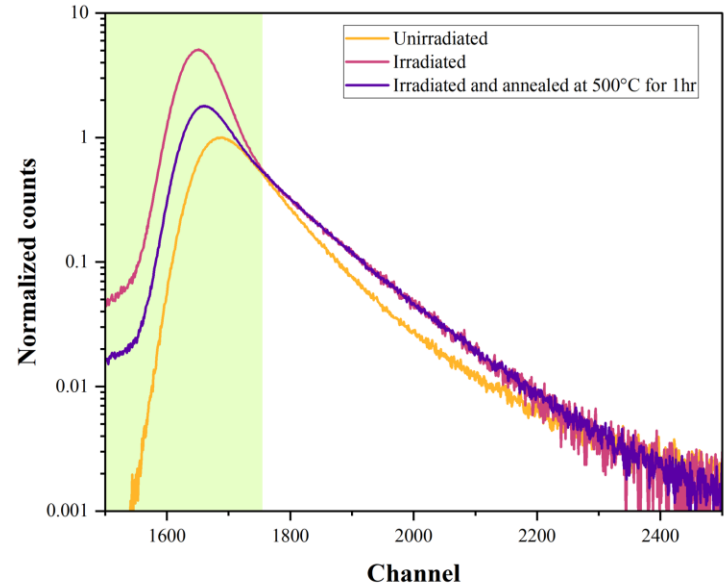


- Bubbles were hard to observe in as-irradiated condition.
- Annealing resulted into detection of bubbles at 1.1 Mx.



- HRTEM and corresponding i-FFT image did not show any disruption in lattice periodicity.
- Rel-rod DF TEM images did not show any sign of faulted loops in UO_2 .

- The spectra of the irradiated samples were normalized by aligning their intensities at channels beyond the affected region.
- The positron lifetime increased after irradiation, suggesting the formation of vacancy-type defects.
- The spectra before and after annealing appear nearly identical.



$\text{UO}_2\text{-UB}_2$	τ_1 (ps)	I_1 (%)	τ_2 (ps)	I_2 (%)
Unirradiated	185	74	380	22.5
Irradiated	290	75	380	22.5
Irradiated + annealed at 500°C for 1hr	289	75	380	22.5

- The burnup of ^{10}B under selected irradiation condition was estimated to be $\sim 0.075\%$ using⁶:

$$F = 1 - e^{-\sigma_a \varphi_{th} t}$$

where, σ_a is the thermal neutron capture cross-section of ^{10}B , φ_{th} is the thermal neutron flux at PULSTAR, and t is the irradiation time.

- Longer irradiation durations would be required to achieve higher ^{10}B burnup – more pronounced damage in both UO_2 and UB_2 phases.
- Despite the low burnup and corresponding low dpa level, He nanobubbles were observed in both phases.

Table 1: Bubble size and density in irradiated-annealed UO₂-UB₂

Phase	Condition	Bubble size (nm)	Bubble density ($\times 10^{23} \text{ m}^{-3}$)
UB ₂	As-irradiated	0.497 ± 0.098	1.353 ± 0.120
UO ₂	As-irradiated	-	-
	Irradiated + 500°C/1hr annealed	0.508 ± 0.085	5.139 ± 0.733
	Irradiated + 500°C/1hr annealed + 1000°C/1hr annealed	0.597 ± 0.090	5.214 ± 0.743

- The irradiated-annealed UO₂ phase still exhibited a substantially higher bubble density than the as-irradiated UB₂ phase.
- The average bubble sizes in the two phases remained comparable.
- Supports the statement that UB₂ are more likely to be implanted into the surrounding UO₂ grains than retained within UB₂.

- He nanobubbles were observed in both UB_2 and UO_2 phases.
- Higher bubble density in UO_2 supports the interpretation that He ions generated in UB_2 are more likely to be implanted into the surrounding UO_2 grains.
- No evidence of dislocation loop formation was found in either phase under the present irradiation conditions.
- PALS analysis revealed an increase in positron lifetime after irradiation, indicating the formation of vacancy type defects.
- More uniform damage profile of this concept may provide a useful approach for self-alpha irradiation studies of bulk boron-containing nuclear fuels and correlate that with fuel's degradation of thermal and mechanical properties

- The manuscript on this work is under preparation
 - Aiming to submit that to the JNM-NSUF special issue.
- Currently working on “**Impact of irradiation induced defect on thermal conductivity of zirconia**” which was awarded on RTE 2025 2nd Call.

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Impact of irradiation induced defects on thermal conductivity of zirconia

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