RaDIATE Collaboration

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Proton Accelerators for Science and Innovation
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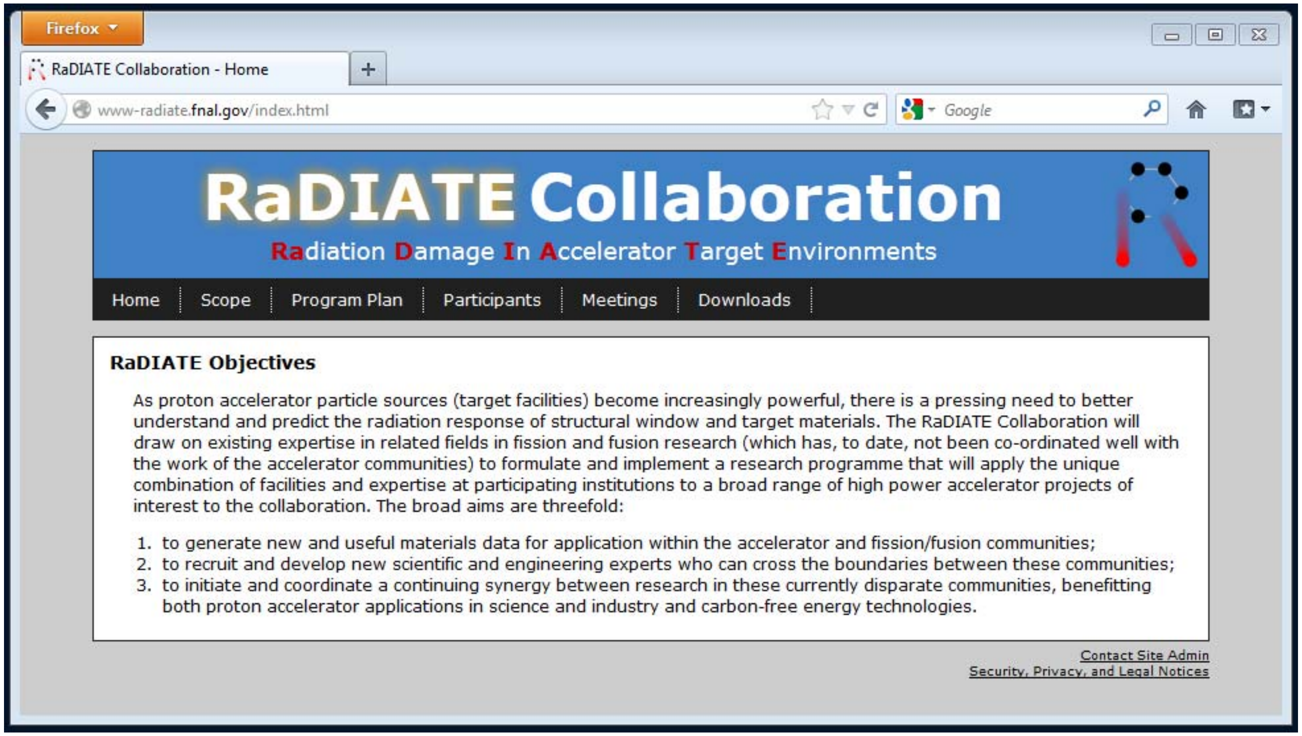
RaDIATE Website



RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

RaDIATE Objectives

As proton accelerator particle sources (target facilities) become increasingly powerful, there is a pressing need to better understand and predict the radiation response of structural window and target materials. The RaDIATE Collaboration will draw on existing expertise in related fields in fission and fusion research (which has, to date, not been co-ordinated well with the work of the accelerator communities) to formulate and implement a research programme that will apply the unique combination of facilities and expertise at participating institutions to a broad range of high power accelerator projects of interest to the collaboration. The broad aims are threefold:

1. to generate new and useful materials data for application within the accelerator and fission/fusion communities;
2. to recruit and develop new scientific and engineering experts who can cross the boundaries between these communities;
3. to initiate and coordinate a continuing synergy between research in these currently disparate communities, benefitting both proton accelerator applications in science and industry and carbon-free energy technologies.

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Web address: : http://www-radiate.fnal.gov/index.html
Listserv address: radiate@listserv.fnal.gov

- Scope and plan of the collaboration
- Presentations and minutes from monthly meetings (5)
- Documents and reports on radiation damage studies
- Irradiated materials table and target parameter space

Stage 1 progress: Exploratory/Development

Stage 1 objective: develop specific research activities to meet program goal!

- ☐ Literature review of material radiation damage studies
  - Graphite, Beryllium and Tungsten
- ☐ Post-doc material of study choice
- ☐ Post-doc recruitment
- ☐ Irradiated specimens and target parameter space
- ☐ Identify existing facilities testing capabilities

Radiation damage literature review

Graphite

- Barry Mardsen and Graham Hall (University of Manchester)
- Radiation damage in nuclear graphite
- Analyzed potential concerns for target environments

Beryllium

- Barry Jones (Oxford University team) to provide an update on Be work
- Lack of radiation damage data on fatigue or irradiation creep

Tungsten

- Barry Jones (Oxford University team) starting to look at Tungsten data in more detail

Material of choice for post-doc studies

Beryllium

- If RaDIATE does not undertake Be radiation damage study, it will not happen anytime soon!
- Research programs on graphite and tungsten already ongoing for nuclear applications
- Broad application as windows in all high intensity machines
- Some experience with Be from fusion research at Culham Center for Fusion Energy (CCFE)
- LBNE funding significant portion of post-doc cost – low Z neutrino target material suitable for LBNE is desired

Post-doc recruitment

- Post-doc to be based at the Materials for Fusion and Fission Power (MFFP) group at Oxford University under Steve Roberts
  - anticipated work at RaDIATE US participating institutions

- Job description for post-doc Be studies finalized

- PO for post-doc costs in process

- Advertising very soon!

Irradiated specimens and parameter space

☐ Updated list of available irradiated specimens

- Be, W, C
- Irradiation environment and proton fluence
  - 0.16 – 400 GeV, 60 - 900 °C, 5e20 – 5e22 p/cm^2
- Estimated DPA damage and gas production
  - 0.1 – 9 DPA, ~ 300 appm/DPA He, ~ 1000 appm/DPA H

☐ Parameter space for RaDIATE program

- Targets/windows of future accelerator facilities
- Expected operating conditions and beam parameters
  - 0.8 – 120 GeV, 300 - 1600 °C, 0.1-20 DPA/yr
- Potential tests/studies required

http://www-radiate.fnal.gov/downloads.html

Potential new collaborators

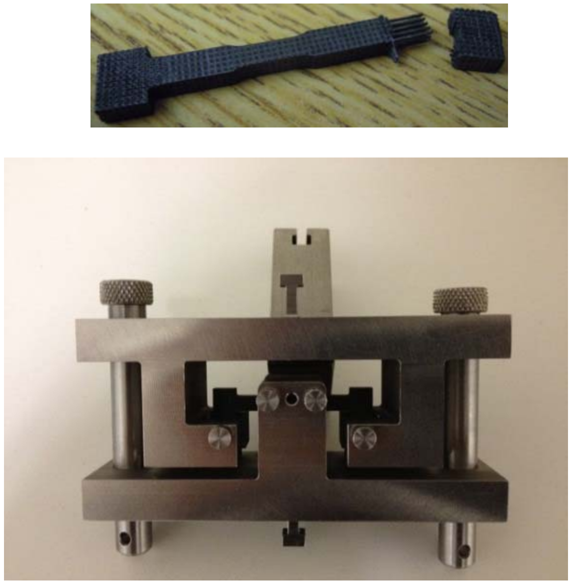
- ☐ FRIB/MSU MatX initiative – Georg Bollen, Frederique Pellemoine
  - Radiation damage from ‘swift ions’ on
    - Graphite target
    - Titanium beam dump vessel
    - Diamond detectors

- ☐ LANL – Stuart Maloy has expressed interest and is on the RaDIATE mailing list

- ☐ ESS Target Facility
  - Tungsten target
  - Beam window

Other news…

- MOU status
  - Approved!
  - Current collaborators: FNAL, STFC, PNNL, BNL, Oxford
- NNUF update from Steve Roberts
  - Currently purchasing equipment
  - Potentially accept activated materials for tests in about 2 years
- BNL BLIP graphite studies
  - HEPA filters and hot cell ready
  - Flexural tests on irradiated 3D C/C composites
- Interim report for Stage 1 complete



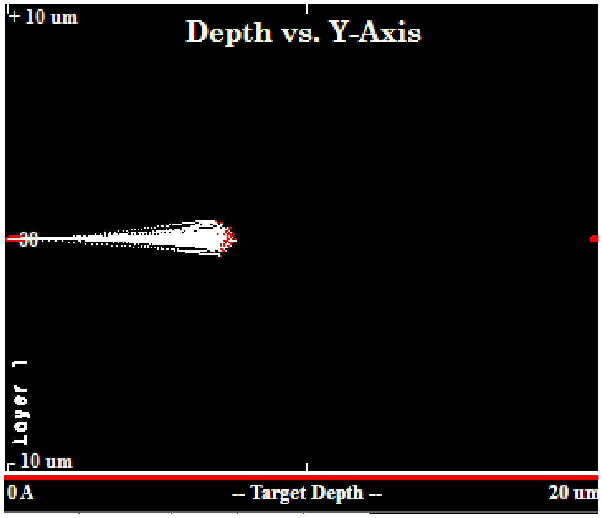
Next steps…

☐ Final report for Stage 1 – Summer 2013

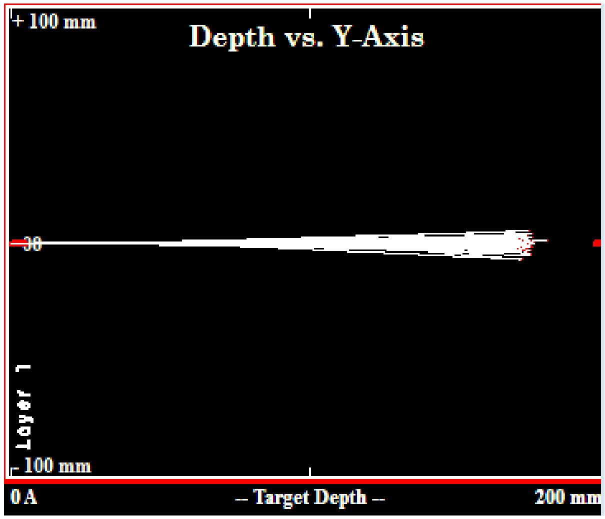
☐ Recruit post-doc by Fall 2013

☐ Evaluate available irradiated specimens and new irradiation testing needs – HE protons vs. LE ions

2 MeV He ions into Be
~ 7 µm penetration



200 MeV protons into Be
~ 180 mm penetration

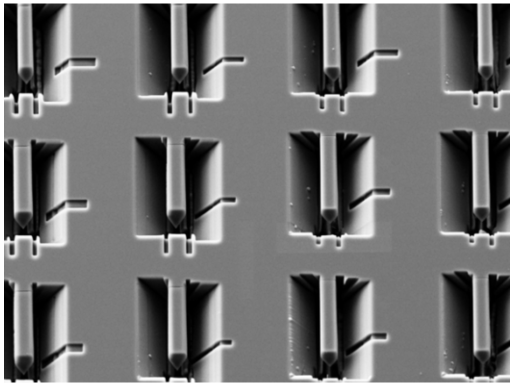


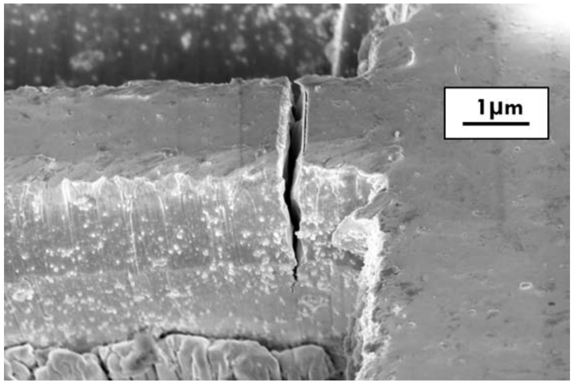
Next steps…

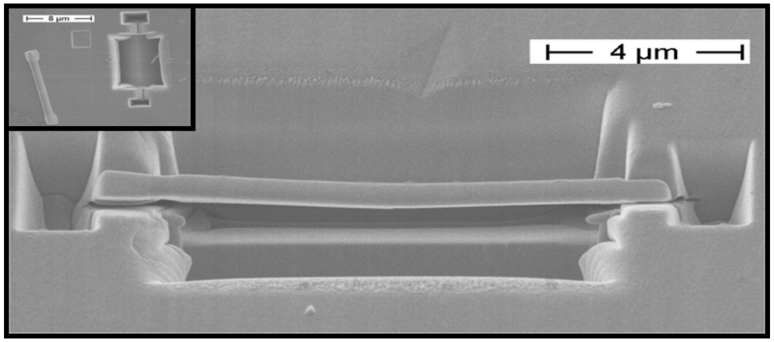
☐ Evaluate Post Irradiation Examination (PIE) techniques to start initial tests on irradiated Be specimens

  ☐ Micromechanics on Be (MFFP group – Oxford)

  - Micro-properties to bulk properties







Opportunities for future collaboration

- Coordinate with FRIB/MSU on MatX initiative
- Graphite: BNL BLIP
- Tungsten: ISIS/RAL
- Open to other collaborators
  - Contact: P. Hurh, C. Densham

Beryllium for proton accelerator windows and targets

By

R B Jones

Irradiation experience on Be

- Design conditions proposed for Be proton accelerator windows and targets.
- Accelerator operating experience with Be.
- Survey of neutron irradiation experience with Be.
- Other factors of importance for Be usage.

Proposed window/target designs

LBNE 700kW, 120GeV, 1Hz, σ_{rms} = 1.3mm Window/target

Cyclic T ºC	*Dose dpa*	*Gas*
200/300	0.15/year total	He 1330 appm/year
Av/peak	@7e-4 to 7e-9dpa.s^{-1}	He/dpa = 8867
	Maximum/average	H data not available

LBNE 2.3MW 120GeV, 1Hz, σ_{rms} = 1.3mm Target only

Cyclic T ºC	*Dose dpa*	*Gas*
350/550	0.5/year total	He data not available
Av/peak	@2.5e-3 to 2.5e-8 dpa.s^{-1}	H data not available
	Maximum/average	

H (Tritium) generation and release needs consideration

Be windows operate in air/vacuum conditions

Accelerator irradiation experience

- Various Be windows, targets & test pieces are available.
- Average operating temps 40º to 200ºC, max peak 250ºC.
- Windows in air/vacuum, targets in air, test pieces in water.
- Pulsed operation 0.5 - 7.5Hz (or a more complex cycle).
- Beams 0.2 - 400 GeV, 0.19 - 1mm spot sizes.
- Peak proton fluences mostly 1.4e21 to 3.7e24 p/cm^2.
- Peak dose (when quoted) 0.1 - 8.5 dpa.
- No gas production values available.
- Two CERN CNGS windows failed after 0.49 - 1.4e20 POT.
- Maximum life 9 and 30 years for another window and target respectively.
- S65, PF-60 and S200F Be grades represented.
- Post-irradiation examination needed for causes of failure.

Data from neutron irradiations

Irradiations cover 43 - 600ºC, doses from <1 - 52 dpa (Be) at dose rates of 0.2 - 9.9 x10^{-7} dpa/s with He contents up to 22,500appm at He/dpa ratios of 50 - 420. Extent of data not equally populated for all phenomena investigated.

Relative to accelerators neutron exposures are at much lower He/dpa ratios and constant dose rates and temperatures. Accelerators have cyclic dose rates and temperatures

Topics investigated (* more details given below)

- *Helium and hydrogen production; bubble swelling
- Irradiation growth
- Irradiation hardening, irradiation embrittlement
- *Fracture toughness
- *Thermal creep, irradiation creep and stress relaxation
- Cyclic stressing
- *Thermal conductivity
- Irradiation induced changes to other physical properties
- Oxidation
- Corrosion

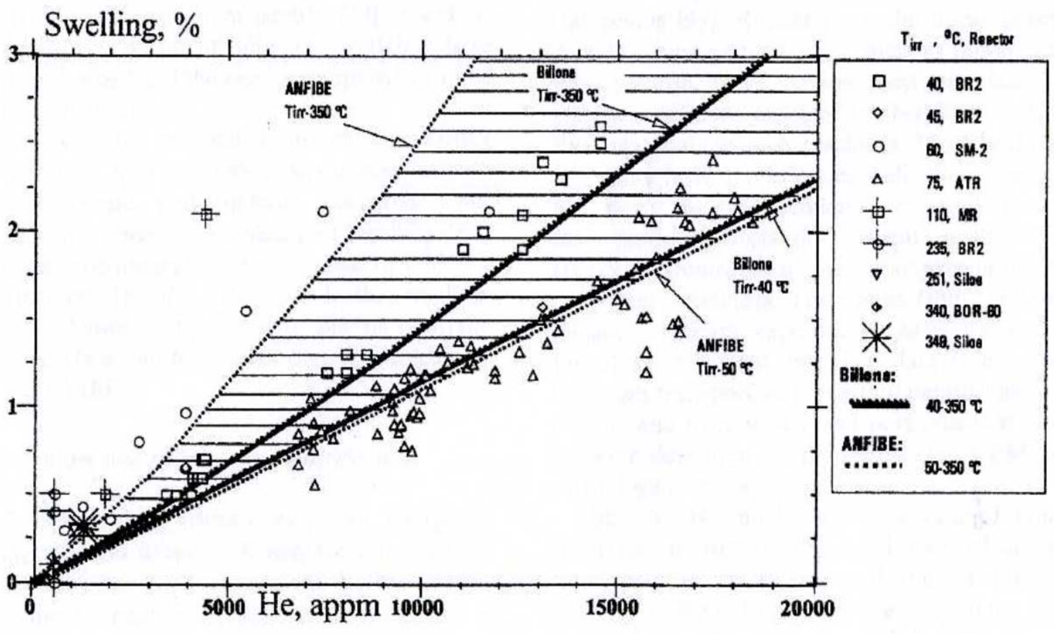
Helium gas and swelling

- Helium arises from ^{9}Be(n, 2n)2^{4}He.
- Large amounts are generated.
- He bubbles give swelling after irradiation at ≥ 200ºC.
- No bubbles ≤200ºC; He accommodated in the Be lattice (solid swelling).
- Figure shows %swelling vs He appm (C) for both regimes.

$\%V/V_0 = 1.15\text{e-}4\ C[1 + 9.49\text{e-}5\ C^{0.5}\ T^{1.5}$ $\exp(-3940/T)]$, (T in ºK, Billone's equ'n).

However – only a few data are from density measurements; length changes often used. He content often calculated, not measured. Older grades of Be show more swelling.

- For He level in LBNE (1330appm/year) swelling is ≤0.5%/year.
- Tritium generated by neutrons but in small amounts (~1% of He). This may diffuse to bubbles or escape at surfaces.



Thermal and irradiation creep of Be

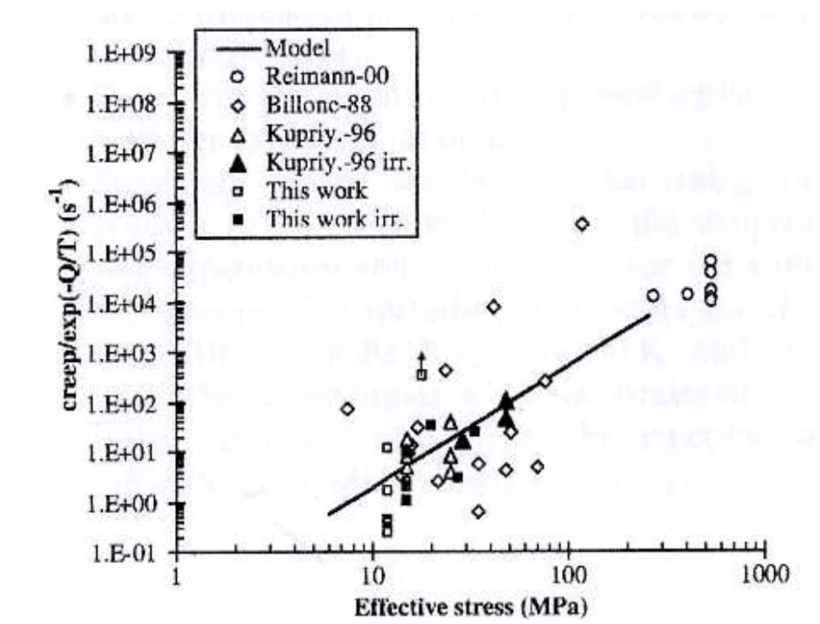
- Thermal creep important $>0.5T_m$ (>504ºC) i.e. at the hot end of Be accelerator usage.
- Wide variations found due to impurities (Al, Mg, Si, Fe), porosity and %BeO.
- Recent data shows steady creep rate ($\sec^{-1}$)

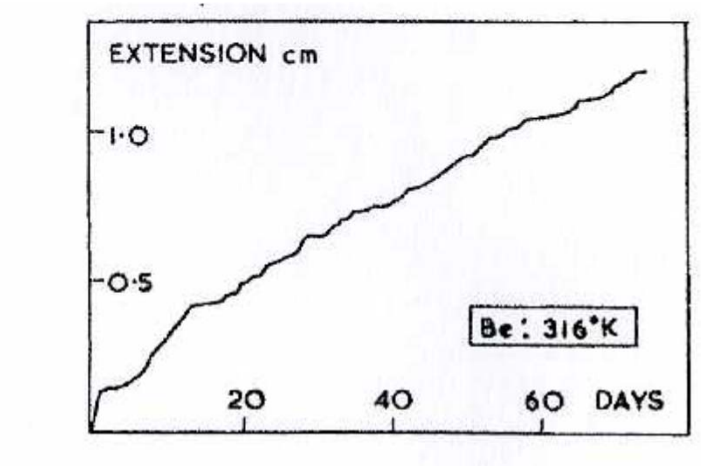
  $\dot{\varepsilon} = A\,(1 - p^{2/3})^{-2.43}\,\sigma^{2.43}\exp(-19470/T)$

  with $A = 7.21\times10^{-3}$ and σ in MPa. This relation incorporates post-irradiation creep for swollen Be (porosity p).
- Concurrent irradiation enhances creep. The lower figure shows a loaded Be helical spring deforming at 43ºC in a MTR (only one test).
- Derived steady state irradiation creep is

  $\dot{\varepsilon}_i = 3.2\times10^{-6}\,(1 - p^{2/3})^{-1}\,(\Phi)\,\sigma$

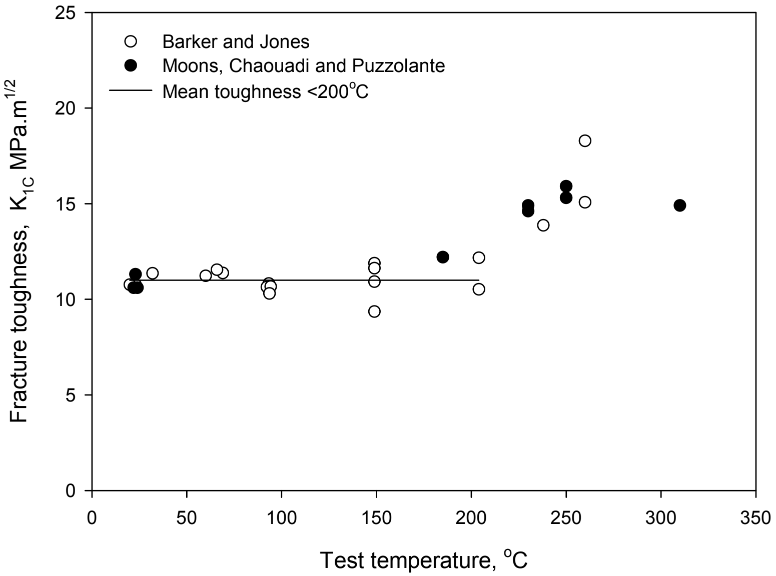
  with Φ in dpa/s and σ in MPa. No primary creep or any later creep from irradiation-induced void or bubble swelling is included
- Stress relaxation can be estimated from the primary and steady creep data.

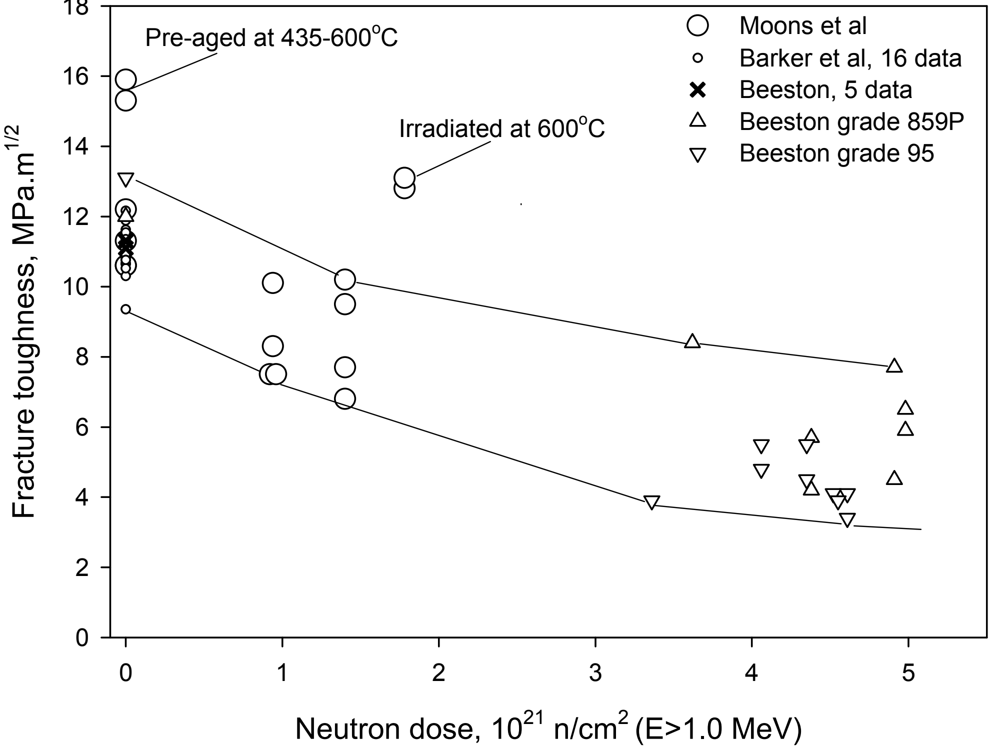




Fracture toughness of Be

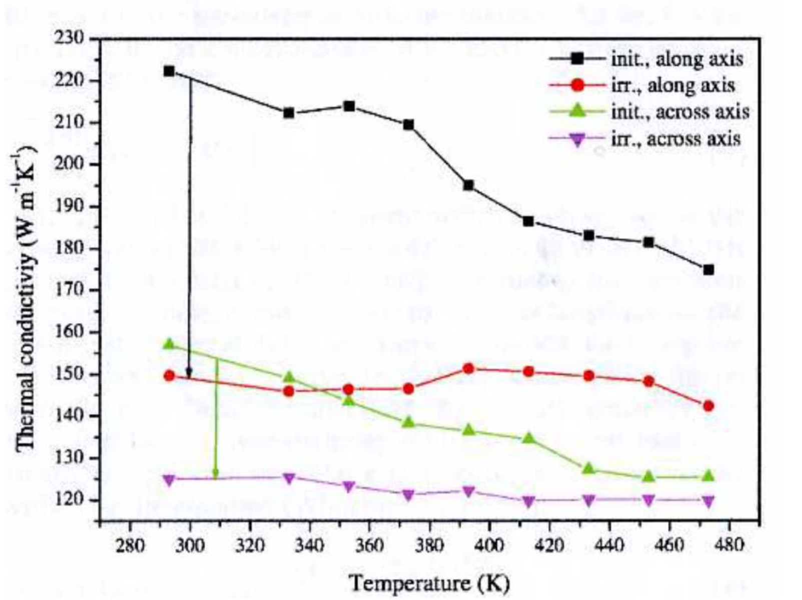
- Differing grades of Be (CIP-HIP, VHP and HIP) with 0.5% to1.6% BeO content were tested.
- All unirradiated Be grades had the same toughness of 11 MPa.m$^{1/2}$ at temperatures <200^{o}C. Toughness increased above ~200^{o}C.
- Irradiations in BR-2 at 200, 230 & 350°C to 0.94 to 1.78 x 10^{21}n/cm^{2} (E>1MeV & He/dpa ratio of 290) degraded toughness (Moons et al).
- Be exposed in ATR at 66°C to 3.4 - 5.0 x 10^{21}n/cm^{2}(E>1MeV) also reduced toughness (Beeston).
- Higher temperature-aged or 600ºC-irradiated Be exhibited better toughness levels before and after irradiation.
- No toughness data at high He levels.

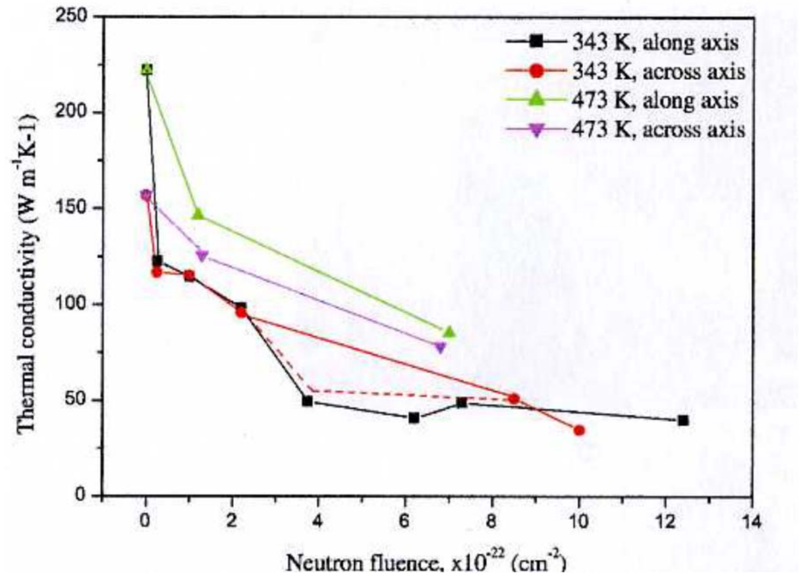




Irradiation and Be thermal conductivity (κ)

- Irradiation effects on κ examined in Be of differing textures, grain sizes and impurity levels (mainly the level of BeO).
- Irradiations were at 343K and 473K, doses of 2 – 58 dpa and He 840 – 20,600 appm (1dpa ~ 0.25 x 10^{22} n/cm^2 (E>0.1MeV).
- κ varies with test temperature and axial orientation (texture). After irradiation at 473K (see top diagram) κ is much reduced, the test temp dependence is lost but texture effects remain.
- The dose-induced reduction in κ after 673K irradiation is much smaller (only 10-20%).
- The most rapid irradiation-induced reduction in κ occurs at the lower doses and irradiation temperatures (lower diagram).
- Prismatic interstitial loops (20-80nm), basal vacancy loops (40-500nm) and He bubbles (4nm) occur (no bubbles below 473K). All loops absent at 673K, only flat plate-like pores seen.
- The reduction in κ at low irradiation temps is mainly due to radiation-induced dislocation loop formation with a contribution from He generation and small He clusters.
- No quantitative analysis has been fully developed relating the type and morphology of the defects present to the observed reductions in κ.
- Need further work at low doses at 473K and on the relative κ effectiveness of transmutation gas.





Other issues

- Irradiation growth in Be has been measured but its magnitude has not been satisfactorily separated from the effects of gas swelling.
- Evidence is available on the release of He and H (T) from Be during heating. He release is not significant below 600ºC.
- Many data exist on irradiation hardening and embrittlement in Be. These effects have their maximum effect at 400ºC.
- No information has been found on the cyclic stressing or creep/fatigue response of irradiated Be.
- Predictive equations are available for the physical properties of Be and the influences of temperature and porosity (e.g. density, Young's modulus, coefficient of thermal expansion).
- Evidence exists for enhanced oxidation of Be under He ion irradiation at ambient temperature. However the significance of this is tempered by the good practical performance of proton-irradiated Be windows in air.
- Long term neutron irradiation increases the corrosion of Be in cooling water.
- Be is not easy to fabricate using conventional techniques which yield textured products. Powder metallurgical methods (HIP) are favoured and can produce products with randomised grain orientations.
- Be is toxic and requires specialised handling (glove boxes, adequate ventilation etc).

Conclusions

- Post-irradiation examination of both failed and unfailed Be windows/targets is required to determine what factors affect longevity under proton irradiation.
- More data required on He and H generation by protons in Be window/targets.
- Determinations of thermal conductivity effects are needed at low irradiation doses and window/target temperatures. Obtain better definition of the κ-effectiveness of He bubbles.
- More Be irradiation creep data needed for estimating stress relaxation of thermal and mechanical stresses.
- Investigation required of pulsed irradiation doses on irradiation creep.
- Experiments needed on cyclic stressing and creep/fatigue of Be both after and under irradiation.
- Need to explore the fracture toughness response of Be at irradiation temperatures between 250 and 600ºC. Determine whether toughness is affected by differing distributions of He bubbles.