Designing High-Performance Radiation-resistant Materials: Recent Progress on Bulk Metallic Glasses

Steve Zinkle

UT/ORNL Governor's Chair,

University of Tennessee and Oak Ridge National Laboratory

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Options for designing radiation resistance

- Three general strategies for radiation resistance can be envisioned:
  - Utilize materials with negligible point defect mobility at desired operating temperatures
    - Amorphization with an accompanying volume change may occur if all point defects are immobile => select temperature range where vacancies are immobile but interstitials are mobile
  - Use materials with intrinsic resistance to radiation damage accumulation (e.g., BCC alloys, high entropy alloys?, noncrystalline materials?)
  - Materials with a high density of nanoscale recombination centers
    - Volumetrically-distributed precipitates or nanolayered structures

Zinkle & Snead, Ann. Rev. Mater. Res. 44 (2014) 241

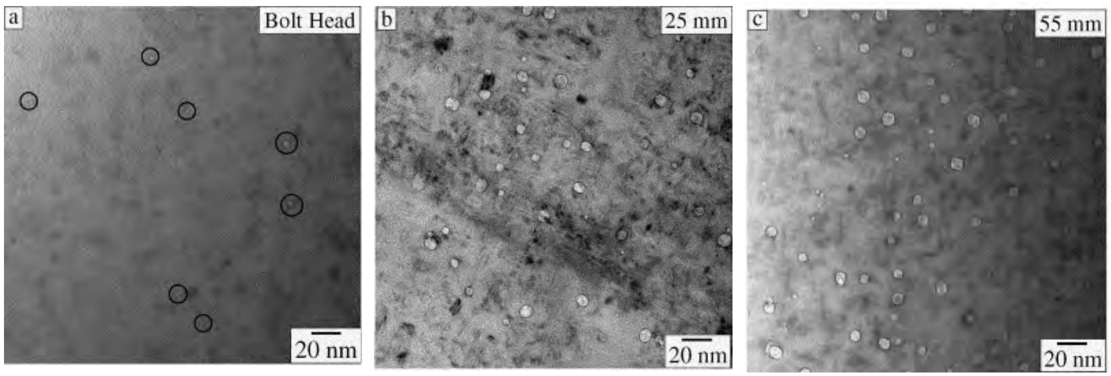
Why explore bulk metallic glasses (BMGs)?

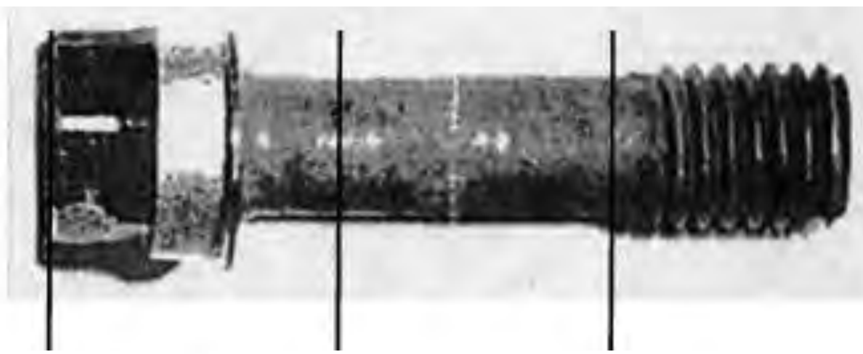
- Recent advances in materials processing now allow relatively large components to be fabricated
  - Unlimited lateral dimensions; several centimeters thick
- Can be cast into near net shapes
- Mechanical properties of BMGs are approaching values historically reserved for steels
  - High strength, high fracture toughness
- Absence of crystalline structure might impart improved radiation stability (no Frenkel pair defects, etc.)
- Tritium trapping at cavities in crystalline materials may be a safety concern for fusion energy
  - Due to the higher free volume in amorphous vs. crystalline solids, He mobility should be enhanced, which could lead to reduced cavities

H retention increases dramatically in the presence of cavity formation

3 to 5x increase in retained hydrogen when cavities are present, even with 2-3x reduction in neutron fluence exposure

500-700 appm H (few cavities) | 1700-3700 appm H (rad.-induced cavities present)





Bolt head
1 mm
320°C, 19.5 dpa

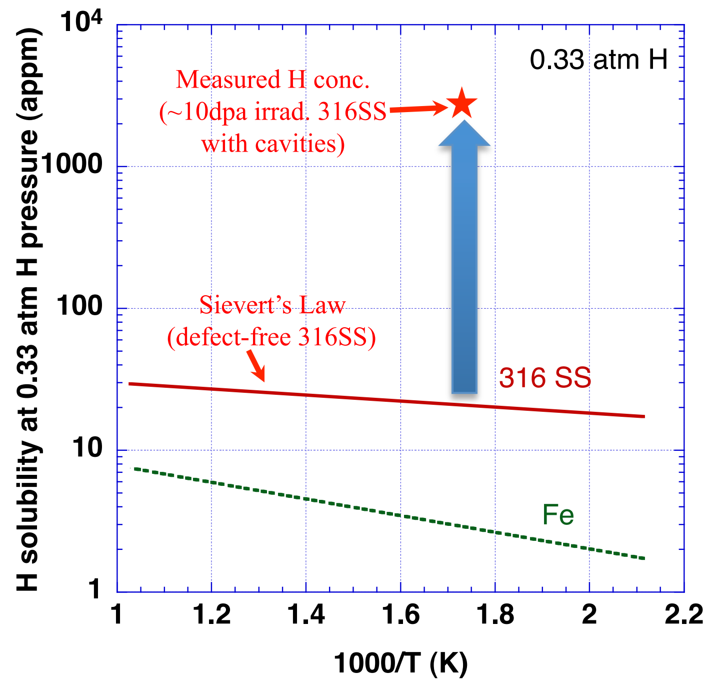
Bolt shank
25 mm
343°C, 12.2 dpa

Near threads
55 mm
333°C, 7.5 dpa

Baffle-former bolt removed from Tihange-1 (Belgium) pressurized water reactor (Type 316 austenitic stainless steel)

F.A. Garner et al., J. Nucl. Mater. 356 (2006) 122

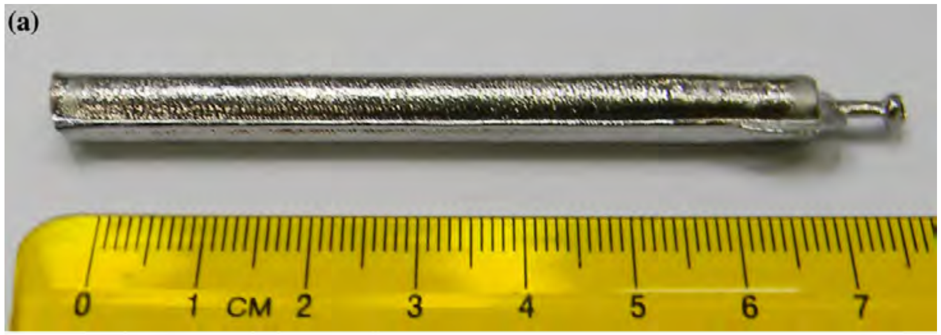
Retained H level is ~100x higher than expected from Sievert's law solubilities

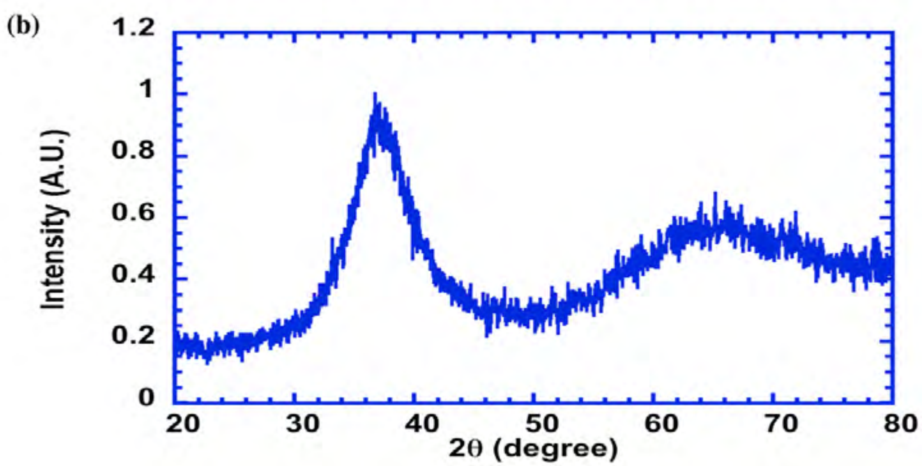


S.J. Zinkle et al., Nucl. Fusion 53 (2013) 104024

BAM-11 bulk metallic glass

a) rod of Zr52.5Cu17.9Ni14.6Al10Ti5 bulk metallic glass prepared by casting and quenching at ORNL and (b) X-ray diffraction pattern showing the amorphous structure

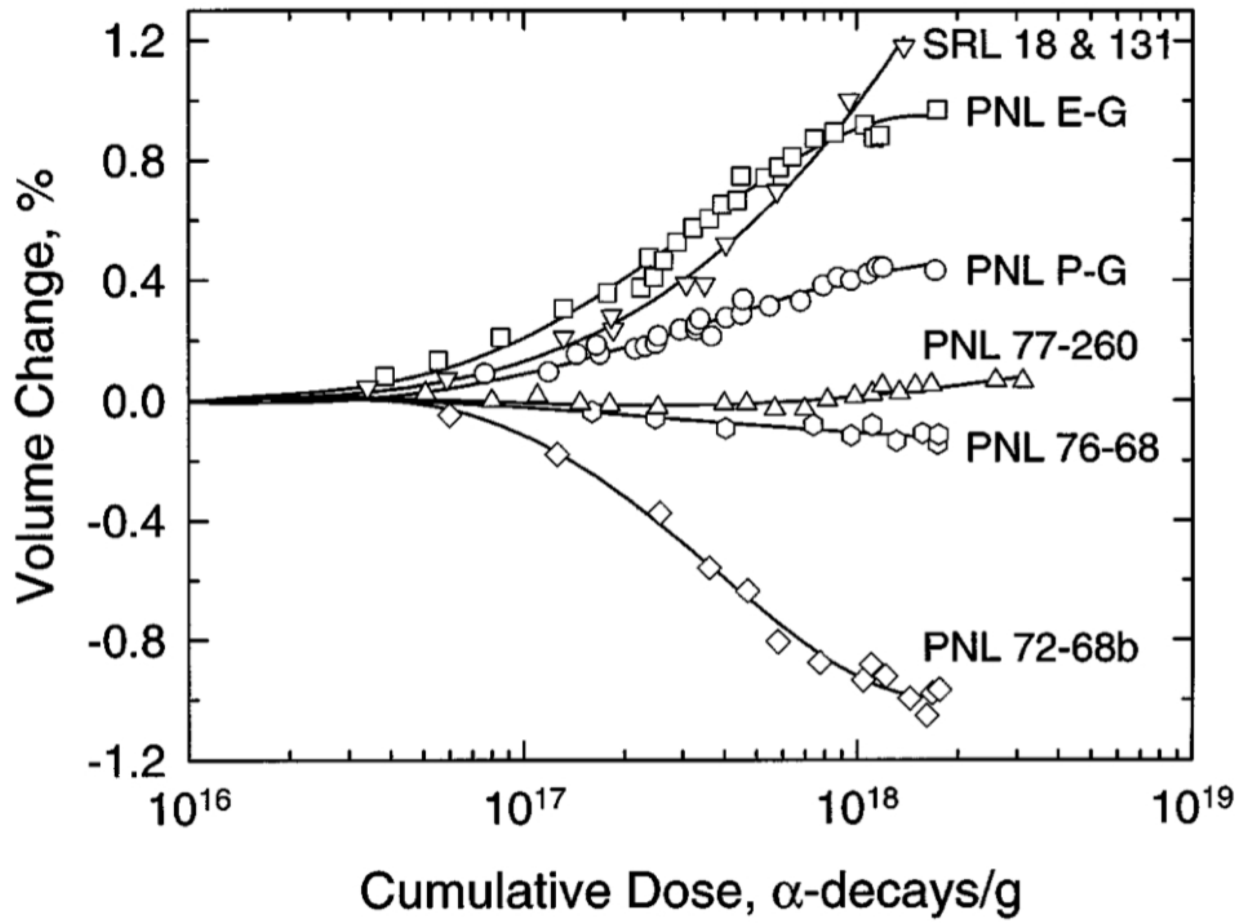




Studies on amorphization of crystalline ceramics have generally observed that the short range order and density of amorphized material is comparable over a wide range of doses, i.e., the material is structurally disordered but chemically ordered (on the molecular scale). In addition, the generally high helium permeability in glasses and the lack of grain boundaries in suitably fabricated bulk metallic glasses may facilitate out-diffusion of helium.

Prior work suggests radiation tolerance of glasses is variable

Volume changes in several actinide-doped nuclear waste glasses

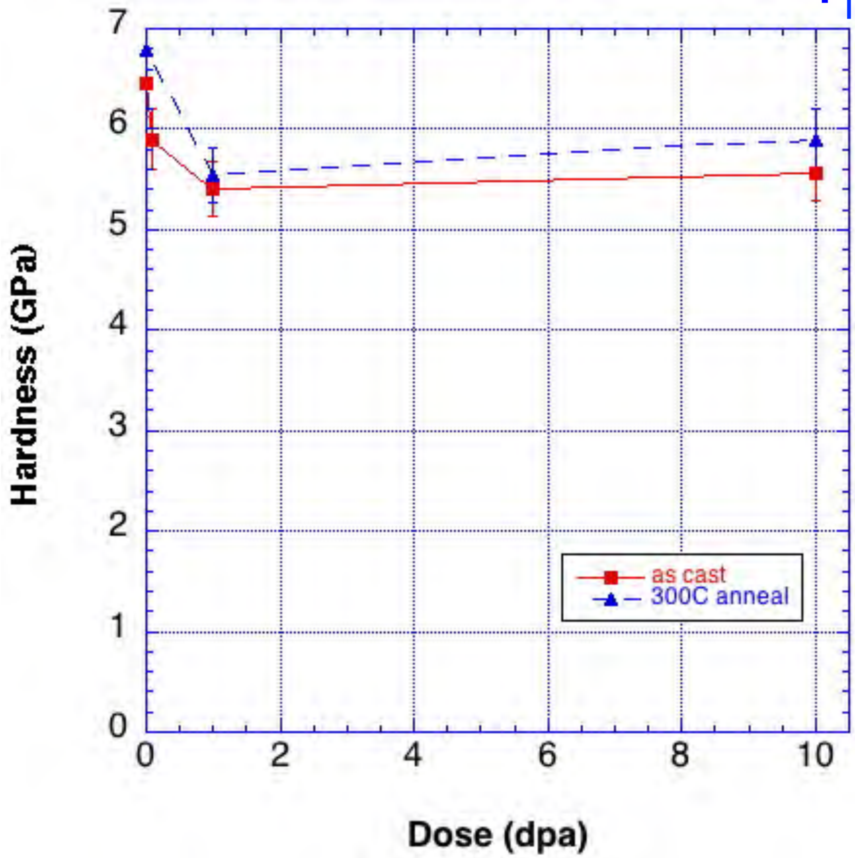


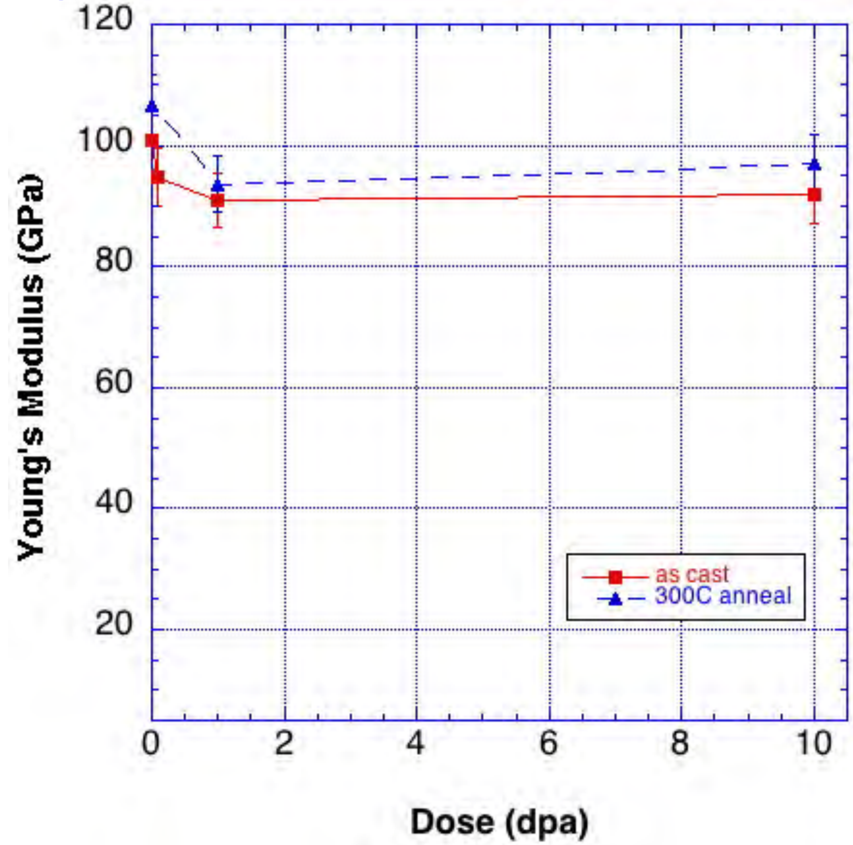
W.J. Weber et al., J. Mater. Res. <u>*12*</u> *(1997) 1946*

Numerous short-range ordered states can occur in glasses; good stability occurs if "radiation-disrupted" SRO is similar to initial SRO

Acceptable stability was observed during ion irradiations of “BAM-11” ($Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_{5}$) glass

3 MeV Ni ion irradiated BAM-11 glass
T_{irr}=25°C





Even smaller changes observed after ion irradiation at 200°C

A. Perez-Bergquist et al. Intermetallics, 53 (2014) 62-66)

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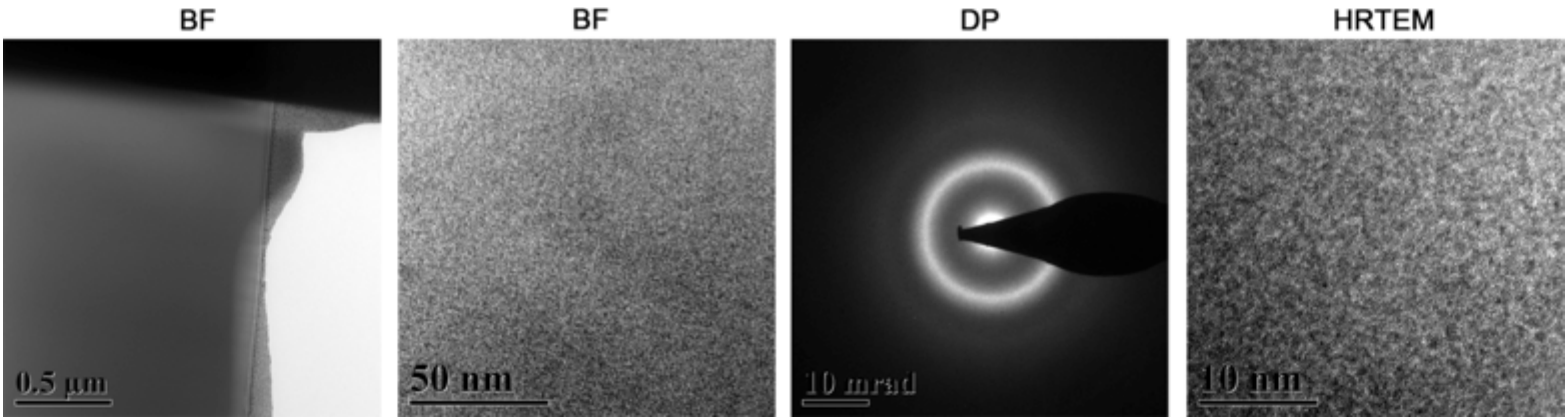
3 MeV Ni ion irrad. BAM-11 glass



No evidence for radiation-induced crystallization of the ion irradiated material

A. Perez-Bergquist et al.
Intermetallics, <u>53</u> (2014) 62-66)

Future work

- **Examination of neutron irradiated samples (0.1, 1 dpa; ~80^{o}C) to obtain bulk physical and mechanical property data**
  - **Volumetric changes**
  - **Flexural strength and elastic modulus**
  - **Fracture toughness**
- **Higher dose (>10 dpa) ion irradiation to explore damage resistance**
- **Examination of He ion implanted BMG specimens to compare He mobility and cavity formation behavior vs. crystalline materials**