Materials Challenges for Generation IV Reactors

Summary / Objectives:

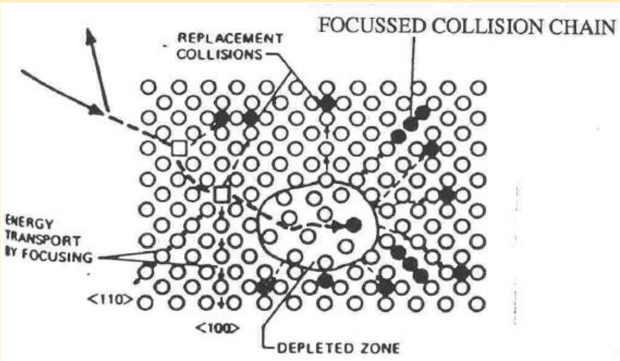
The Generation IV reactors offer significant advantages over typical light water reactors including increased power conversion efficiency, passive safety features and in some cases process heat for other applications (e.g. hydrogen production). These families of reactors include 3 fast reactors [sodium fast reactor (SFR), lead fast reactor (LFR) and gas-cooled fast reactor (GFR)], one thermal reactor [very high temperature reactor (VHTR)] and two fast or thermal reactors [supercritical water reactor (SCWR) and molten salt reactor (MSR)]. The extreme environments in these families of reactors create significant challenges to materials ranging from high doses from a fast neutron flux (SFR, LFR, GFR, SCWR and MSR), more corrosive environments from molten salt (MSR) or lead coolants (LFR) and high temperatures in the helium-cooled reactor concepts (e.g. GFR and VHTR). This presentation will discuss the materials challenges in Generation IV reactor concepts and summarize radiation effects in reactor metals proposed for these concepts over prototypic irradiation conditions

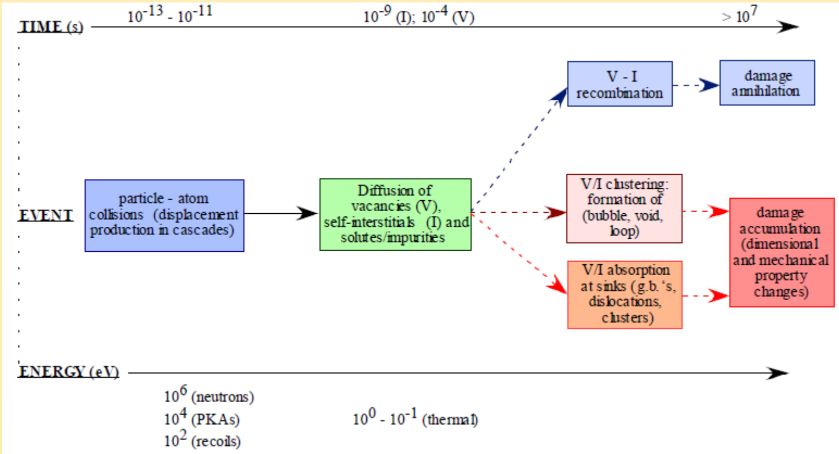
Meet the Presenter:

Stuart Maloy is a Team Leader for MST-8 (materials at radiation and dynamic extremes) at Los Alamos National Laboratory and is the advanced reactor core materials technical leader for the Nuclear Technology Research and Development's Advanced Fuels campaign and the NEET Reactor Materials Technical Lead for DOE-NE.
He has applied his expertise to characterizing and testing the properties of metallic and ceramic materials in extreme environments such as under neutron and proton irradiation at reactor relevant temperatures. This includes testing the mechanical properties (fracture toughness and tensile properties) of Mod 9Cr-1Mo, HT-9, 316L, 304L, Inconel 718, Al6061- T6 and Al5052 after high energy proton and neutron irradiations using accelerators and fast reactors.

Radiation Damage :

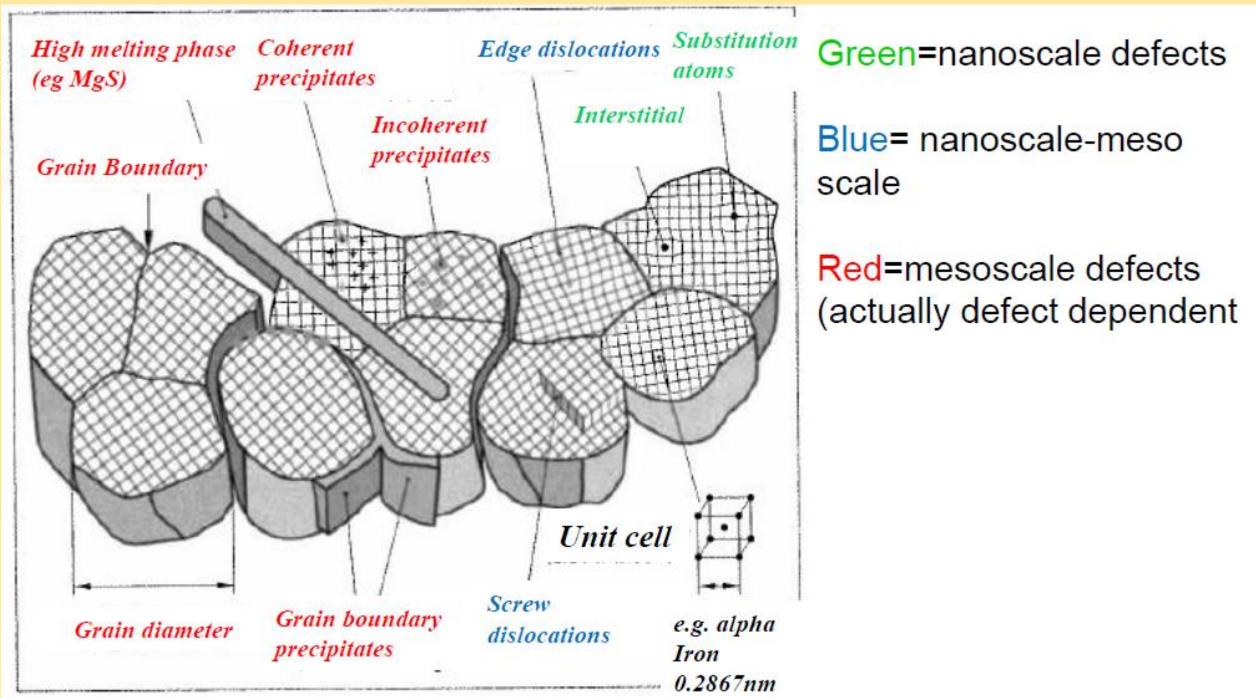
Displacement damage occurs when enough energy (approximately 25 eV) is transferred to an atom producing a or many Frenkel defects. Though a large number of Frenkel defects (vacancy / self-interstitials) annihilated in short time, some defects remain and make cluster.





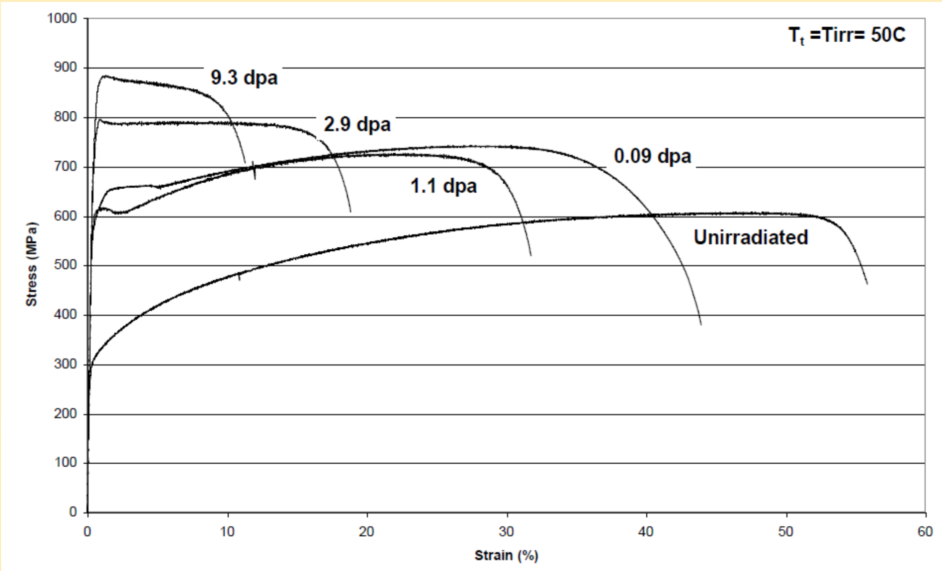
A wide range of materials properties are determined on the mesoscale :

As the result of the clustering, the accumulated defect grows to mesoscale. Unlike with nanoscale defects, mesoscale defects affect the various material properties. This is the mechanism of the radiation damage.



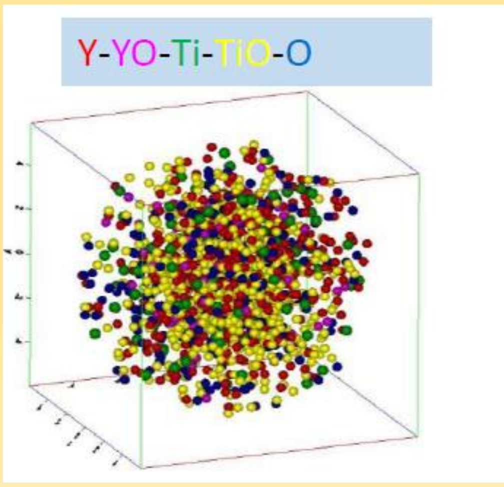
Stress/Strain curves of 316L stainless steel after irradiation :

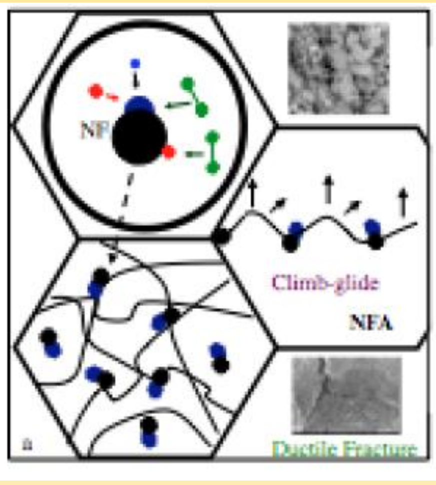
By the irradiation, yield stress of 316L stainless steel is increased (hardening) and elongation is decreased (embrittlement).

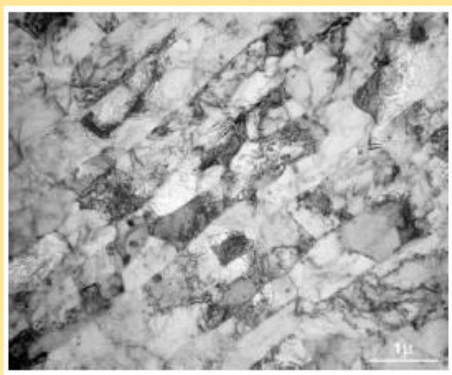


Nanostructured Ferritic Alloys :

Nanostructured ferritic alloys (or Oxide Dispersion Strengthen alloys, ODS) , which is made by mechanical alloying, have a fine distribution of oxide particles nano features within the material. This nanostructure brings increase of the strength, creep resistance, irradiation resistance. Therefore, these alloys show promise as advanced radiation tolerant materials.







Reactor operating conditions :

Each GIF systems have particular operating conditions:

- Coolant
- Temperature
- Lifetime Dose

Reactor Type	Fuel Materials	Fuel Temperature	Pellet to Clad bond	Coolant Type	Structural Materials for Core Internals	Lifetime Dose (dpa)	Structural Temperatures
Gen IV/ Lead Fast Reactor LFR	U/PuN; TRUN (enriched to N^{15})	500-600C	Lead	Pb or LBE	Ferritic/Martensitic Steel alloys	150-200	400-600C
Gen IV/ Sodium Fast Reactor SFR	Metal(U-TRU-10%Zr Alloy), MOX(TRU bearing)	600-800C (metal fuel) 800-2000C (Oxide fuel)	Sodium	Sodium	Ferritic/Martensitic Steel alloys	150-200	400-550C
Gen IV/ Gas cooled Fast Reactor GFR	UPuC/SiC (50/50%) with 20% Pu content ; Solid Solution fuel with SiC/SiC cladding	2000 +	Helium	Helium	Nickel Superalloys /Ceramic Composites	80	500-1200C
Fusion Energy	N/A	N/A	N/A	Pb-Li	F/M steels; Vanadium alloys; Ceramics	150	300-1000C
LWR – PWR, BWR	UO2	800-1600C	Helium	Water	316L.ferritic pressure vessel, Zircalloy cladding	Cladding ~10 dpa, Internals up to 80 dpa	200-300C
Very High Temperature Reactor (VHTR, NGNP)	TRISO	800-2000C	Intimate contact	Helium	Ni-based alloys, ceramics and graphite	~10 dpa	700-1000C
Supercritical Water Reactor (SCWR)	UO2	800-2000C	Helium	Water	F/M steels, austenitic steels	10-30 thermal 100-150 Fast	300-600C
Molten Salt Reactor (MSR)	Na, Zr, U, Pu fluorides	700-800C	N/A	N/A	Ni-based alloys, graphite	100-150 dpa	600-800C

Materials Performance Issue :

Because of the difference of operating condition, each GIF systems have particular material performance issues.

Reactor type	Primary Materials	Performance Issues
Light Water Reactors (PWR/BWR)	Ferritic pressure vessel steels, Fe-based austenitic stainless steels, zirconium alloys	IGSCC, IASCC, Fuel clad mechanical interaction, hydriding, Radiation embrittlement (DBTT), hydrogen embrittlement
Very High Temperature Reactor (VHTR)	Ni-based superalloys, Graphite, ferritic/martensitic steels, W/Mo Alloys, SiC/SiC composites	Helium embrittlement, creep strength, swelling, RIS, transmutation, toughness, oxidation
Sodium Fast Reactor (SFR)	Fe-based austenitic SS, Ferritic/martensitic steels,	Radiation Embrittlement (DBTT), toughness, helium embrittlement, swelling, RIS, corrosion, FCCI
Lead Fast Reactor (LFR)	Fe-based austenitic SS, Ferritic/martensitic steels,	Radiation Embrittlement (DBTT), toughness, helium embrittlement, swelling, RIS, corrosion, FCCI, liquid metal embrittlement
Supercritical Water Reactor (SCWR)	Ferritic pressure vessel steels, Fe-based austenitic stainless steels, zirconium alloys, ferritic/martensitic steels	IGSCC, IASCC, Fuel clad mechanical interaction, hydriding, Radiation/helium embrittlement (DBTT), swelling, RIS, corrosion, toughness
Gas Fast Reactor	Ceramics (carbides, nitrides), ceramic composites, nickel superalloys	Helium embrittlement, creep strength, swelling, RIS, transmutation, toughness, oxidation
Molten Salt Reactor	Ni-based alloys, graphite, coatings	Corrosion, Helium embrittlement, creep strength, swelling, RIS, transmutation, toughness, oxidation