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Materials for Nuclear Power: A Brief Introduction

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> *"It is only a paper reactor until the metallurgist tells us whether it can be built and from what."*
>
> \- Norman Hilberry, Director, Argonne National Laboratory, 1957 to 1961

> *"Basic phenomena which require attention are changes in dimensions and properties…, lower ductility of construction materials when irradiated,...high-temperature aqueous corrosion of metals and other topics under the heading of physical metallurgy...."*
>
> \- J. P. Howe, first AIME Nuclear Metallurgy Symposium, 1955

Materials are at the forefront of nuclear power. It was true for Generation I reactors in the 1950's and will remain true for tomorrow's Generation III+ and IV reactors.

The nuclear industry presents unique challenges for materials, ranging from microstructural processes to long-term component integrity. The following sections, therefore, introduce some of the effects of irradiation on materials, including:

- Irradiation Effects on Microstructures
- Irradiation Effects on Dimensional Stability
- Irradiation Effects on Mechanical Properties
- Corrosion Issues in Nuclear Power
- High-Level Nuclear Waste Storage

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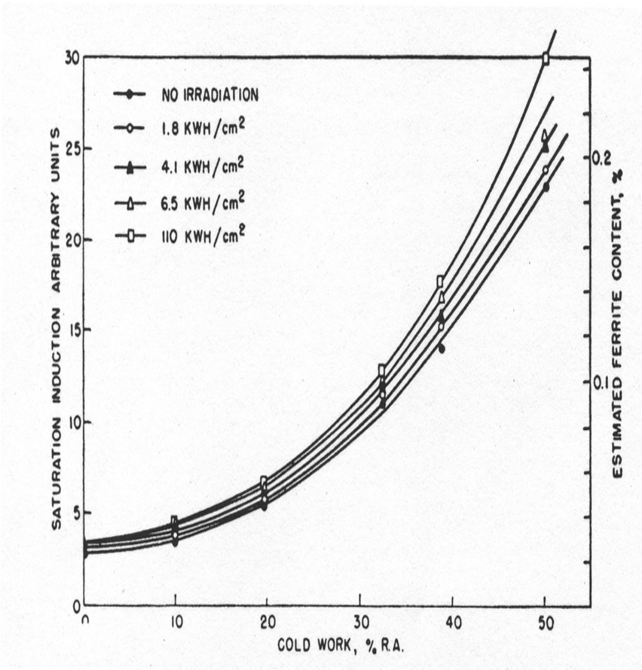

Figure 1: Effect of neutron irradiation on the stability of austenite in type 347 stainless steel. [1]

Irradiation Effects on Microstructures

Changes in mechanical properties and dimensional stability in neutron irradiated materials is related to microstructural changes such as the formation of voids, loop, and precipitates.

Neutron irradiation can also affect the stability of austentite in stainless steel as shown in Figure 1. Irradiation promotes the growth of ferrite, with the effect increasing with greater levels of cold work.

Irradiation can also alter grain boundary composition as shown in Figure 2. In general, irradiation can cause an inverse Kirkendall segregation in which slow diffusing elements (e.g., nickel) enrich grain boundaries and faster moving solutes (e.g., chromium) are depleted from the near-grain boundary regions.[2,3]

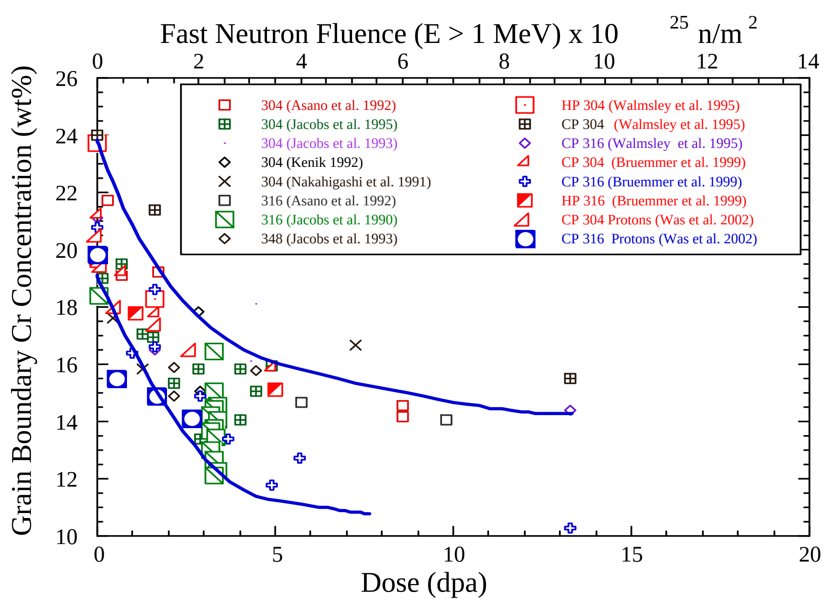

Figure 2: Effect of irradiation on grain boundary composition (300-series austenitic stainless steel). [2]

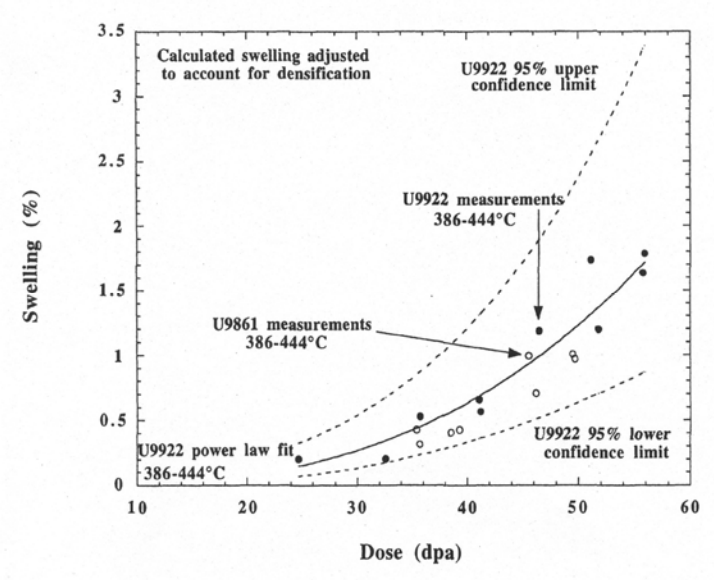

Figure 3: Swelling as a function of temperature for two EBR-II 316 stainless subassemblies.[4]

Irradiation Effects on Dimensional Stability

Irradiation-induced void formation can produce density changes, potentially resulting in dimensional changes in reactor components. Swelling has been observed in metals (see Figure 3) as well as in ceramics. Mitigation requires modifications to material design (e.g., alloying, etc.) or selection.[5] Creep and associated stress relaxation can cause unwanted dimensional changes but can also relieve stresses due to swelling in constrained systems.[6]

Irradiation Effects on Mechanical Properties

Neutron irradiation can result in increased strength and a corresponding decreased toughness as shown in Figures 4 and 5. These trends are associated with the development of dislocation loops, precipitates and voids.[2] Irradiation-induced grain boundary compositional changes can also lead to brittle, intergranular fracture.[9]

Helium generated due to nuclear transformation reactions can diffuse to grain boundaries. Bubbles can subsequently form, especially in structures under a tensile load. This can result in helium embrittlement and a reduction in creep resistance.[10]

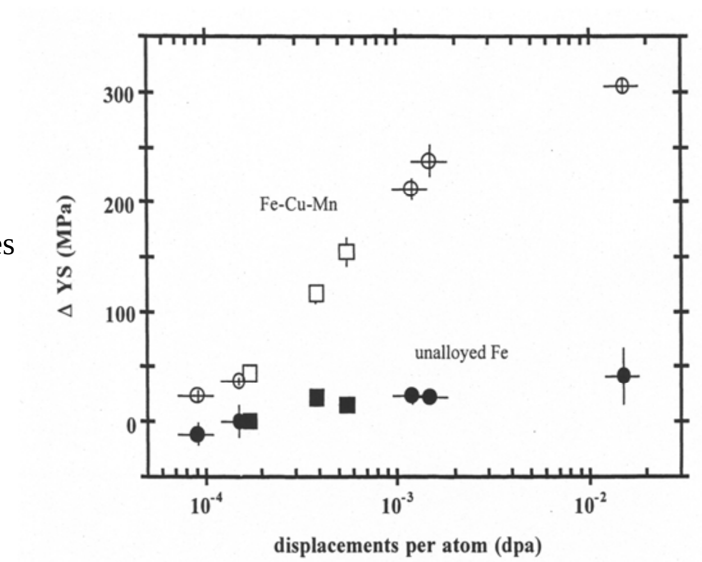

Figure 4: Effect of irradiation on yield strength of iron and steel.[7] (dpa is the average number of displacements per atom due to irradiation)

The damage regions typical of radiated materials are outlined in Figure 6. The prevalent damage mechanisms under service conditions must be considered to prevent component failure.

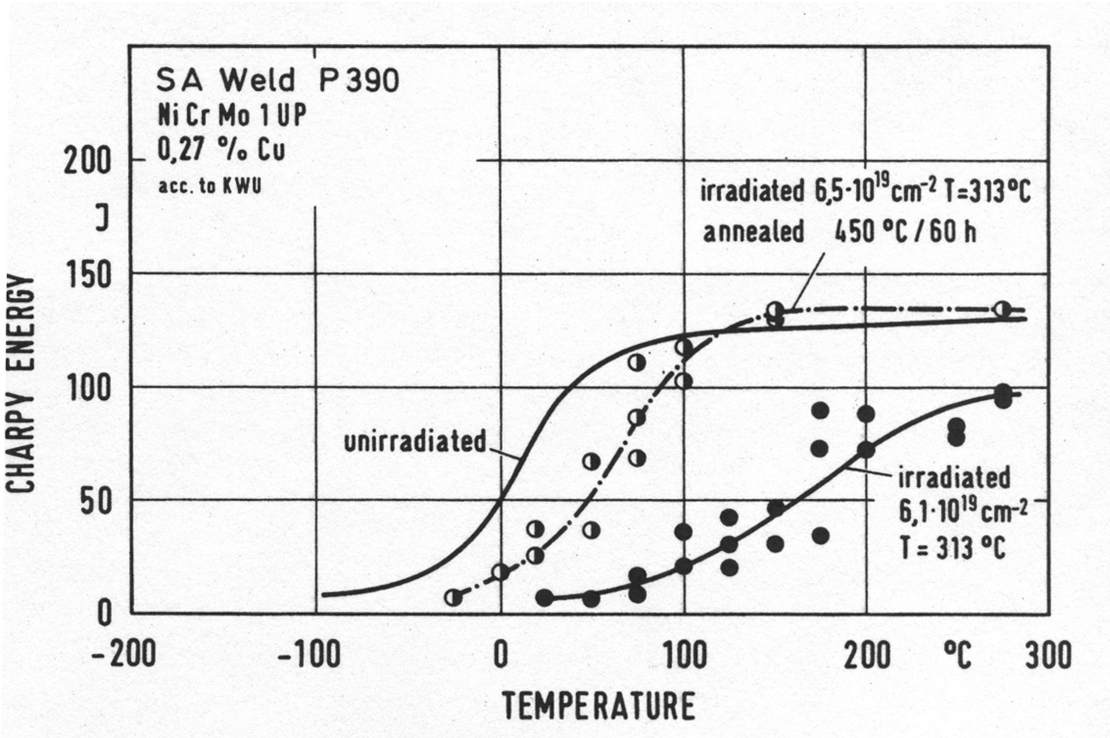

Figure 5: Irradiation causes a decrease in toughness of welded joint making failure likely at higher temperatures. [8]

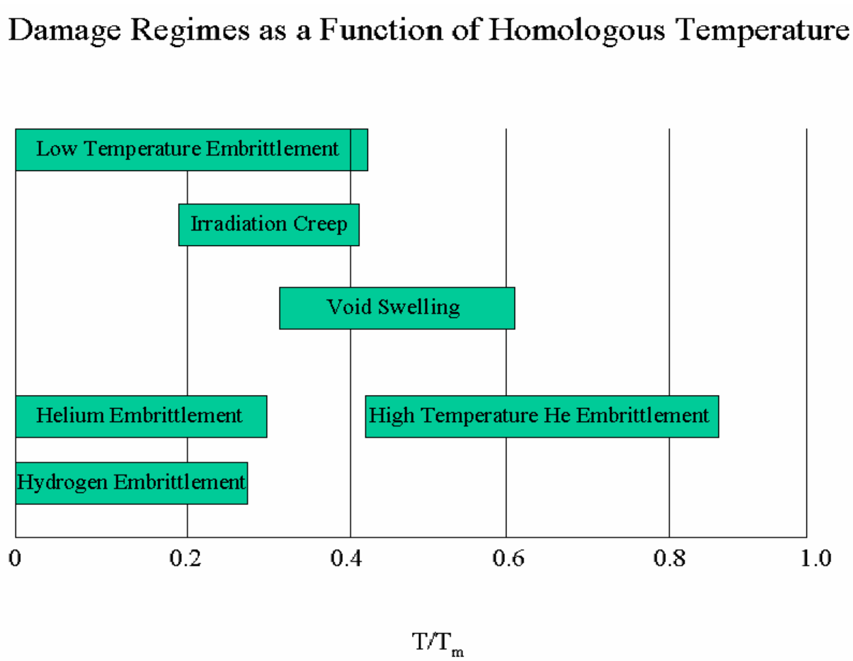

Figure 6: Damage mechanisms for metals as a function of temperature. [11]

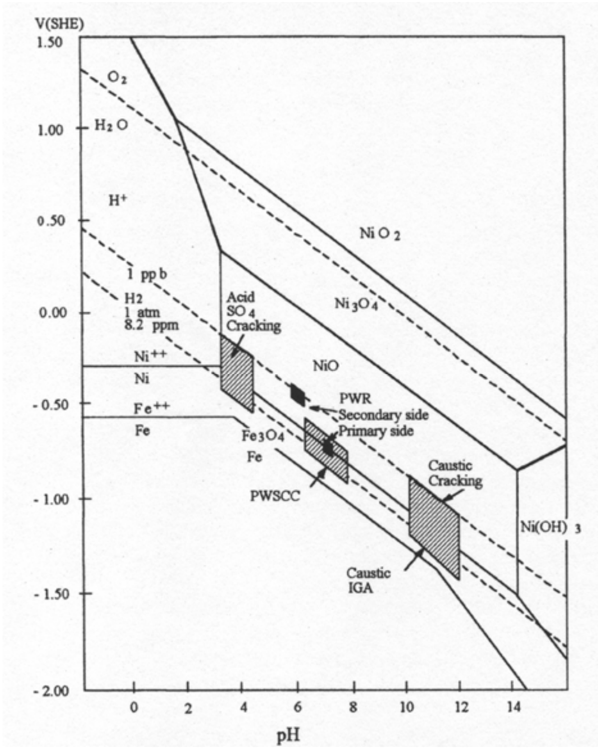

Figure 7: Pourbaix diagram for nickel-based alloy 600 in an aqueous solution (300 ^{o}C) [12]

Corrosion Issues in Nuclear Power

Corrosion-related phenomena remain important for material developments. Figure 7 presents a Pourbaix diagram for a nickel-based alloy, showing internal oxidation products observed in stress corrosion cracking studies.

Figure 8 highlights the role of irradiation in promoting intergranular stress corrosion cracking. Irradiated assisted stress corrosion cracking (IASCC) is likely related to both irradiation hardening and grain boundary composition changes mentioned above. Additionally, radiation can also affect the water chemistry, potentially resulting in a more aggressive environment. [14]

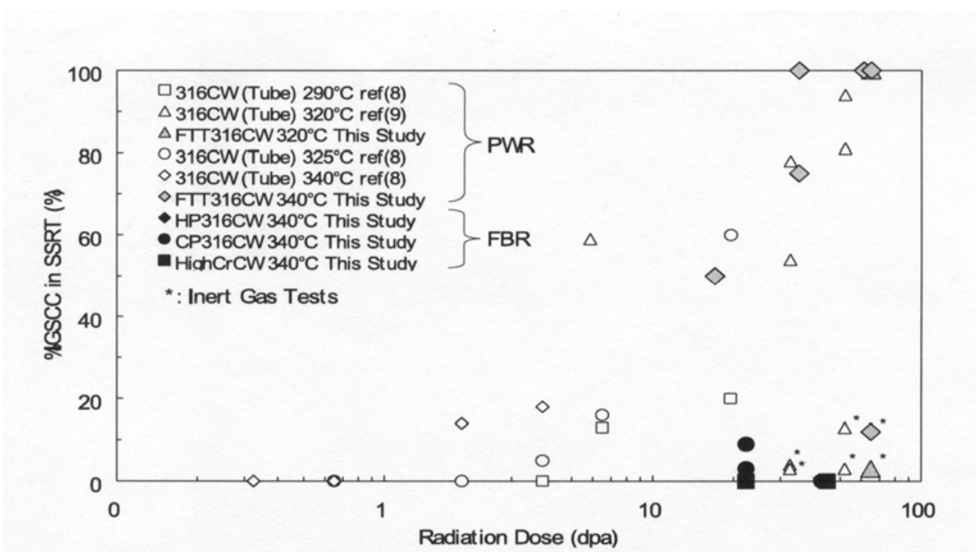

Figure 8: Effect of radiation dose on percentage of intergranular stress corrosion cracking for materials irradiated in boiling water reactors (BWR) and fast breeder reactors (FBR) and tested in PWR water. [13]

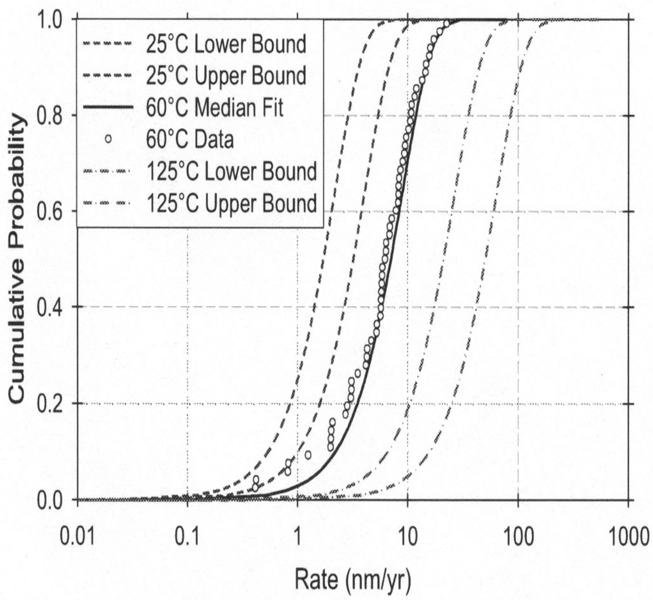

Figure 9: General corrosion rate for Alloy 22 waste package outer barrier. [15]

High-Level Nuclear Waste Storage

Long-term nuclear waste repositories will require containment system stability for greater than 10,000 years.[15,16] As such, corrosion studies for candidate materials, such as Alloy 22 in Figure 9, are critical. General corrosion, hydrogen induced cracking and stress corrosion cracking data is being extrapolated over the 10,000 year specified timeframe based upon estimated environmental conditions (e.g., ionic species accumulation, microbial activity, radiation-induced degradation, thermal conditions, etc.).

Want to Learn More?

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