LWRS

Light Water Reactor Sustainability

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Light Water Reactor Sustainability: Materials Aging and Degradation

NEUP Workshop

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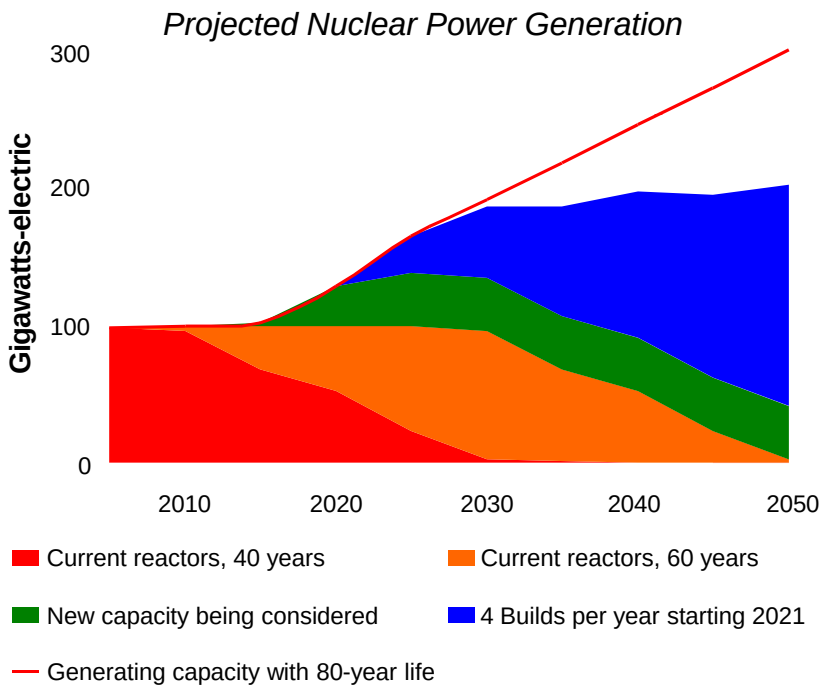
The National Interest

- EIA AEO 2009 reference case has U.S. electricity demand expected to increase ~24% by 2030
  - Annual CO2 emissions projected to increase by 296 million metric tons to a total of 2,729
- Nuclear generation is critical to:
  - Reduce greenhouse gases
  - Meet electricity demand
  - Ensure energy supply security and grid reliability
  - Stabilize energy prices
- Current nuclear plants retire between 2029 – 2056
  - New nuclear build rate will not replace plant retirements
  - Cost to replace the current fleet exceeds $600B
  - Steep reduction in emission-free generation
- Existing reactors reduce burden of new clean electricity that will need to come online



R&D Objective 1: The LWR Sustainability (LWRS) R&D Program

Vision

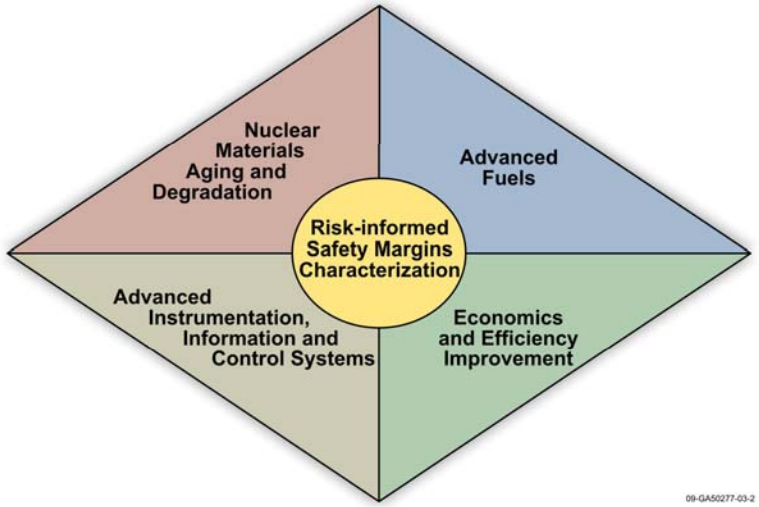
- Enable existing nuclear power plants to **safely** provide **clean** and **affordable** electricity beyond current license periods (beyond 60 years)

Program Goals

- Develop fundamental **scientific** basis to allow continued **safe long-term** operation of **existing** LWRs
- Develop technical and operational improvements that contribute to long-term **economic** viability of existing nuclear power plants

Scope

- Materials Aging and Degradation
- Risk-Informed Safety Margin Characterization
- Efficiency improvements
- Advanced Instrumentation and Controls
- Advanced Fuel Development
- *Energy Innovation M&S Hub*



Materials issues are a key concern for the existing nuclear reactor fleet

- **Materials research is already a key need for the existing nuclear reactor fleet**
- **Materials degradation can lead to increased maintenance, increased downtime, and increased risk.**
- **Materials issues must be resolved for:**
  - Reactor Pressure Vessels and Primary Piping
  - Core Internals
  - Secondary System
  - Weldments
  - Concrete
  - Cabling
  - Buried Piping

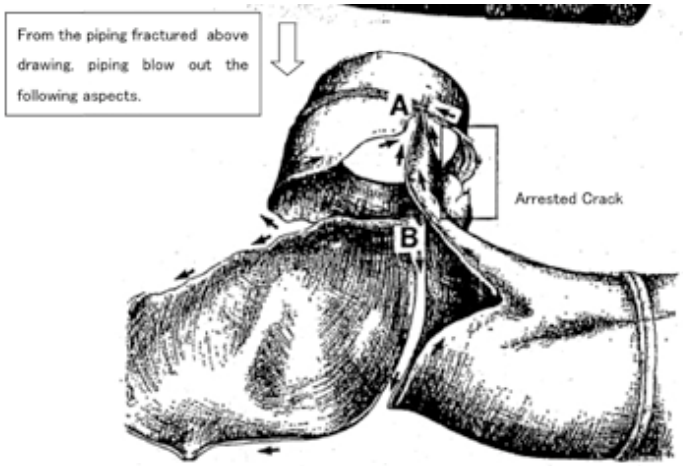
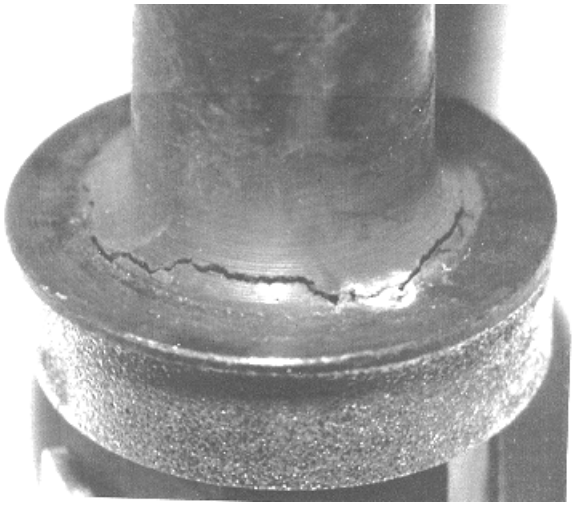


Fig.3 Detail Drawing of the Breaking Portion

Extension of service life may cause new challenges for materials service

- **Materials research is already a key need for the existing nuclear reactor fleet**
- **Increased lifetime leads to increased exposures**
  - Time at temperature
  - Stress
  - Coolant
  - Neutrons
- **Extending reactor life to 40, 60 years or beyond will likely increase susceptibility and severity of known forms of degradation**
- **New mechanisms of materials degradation are possible**

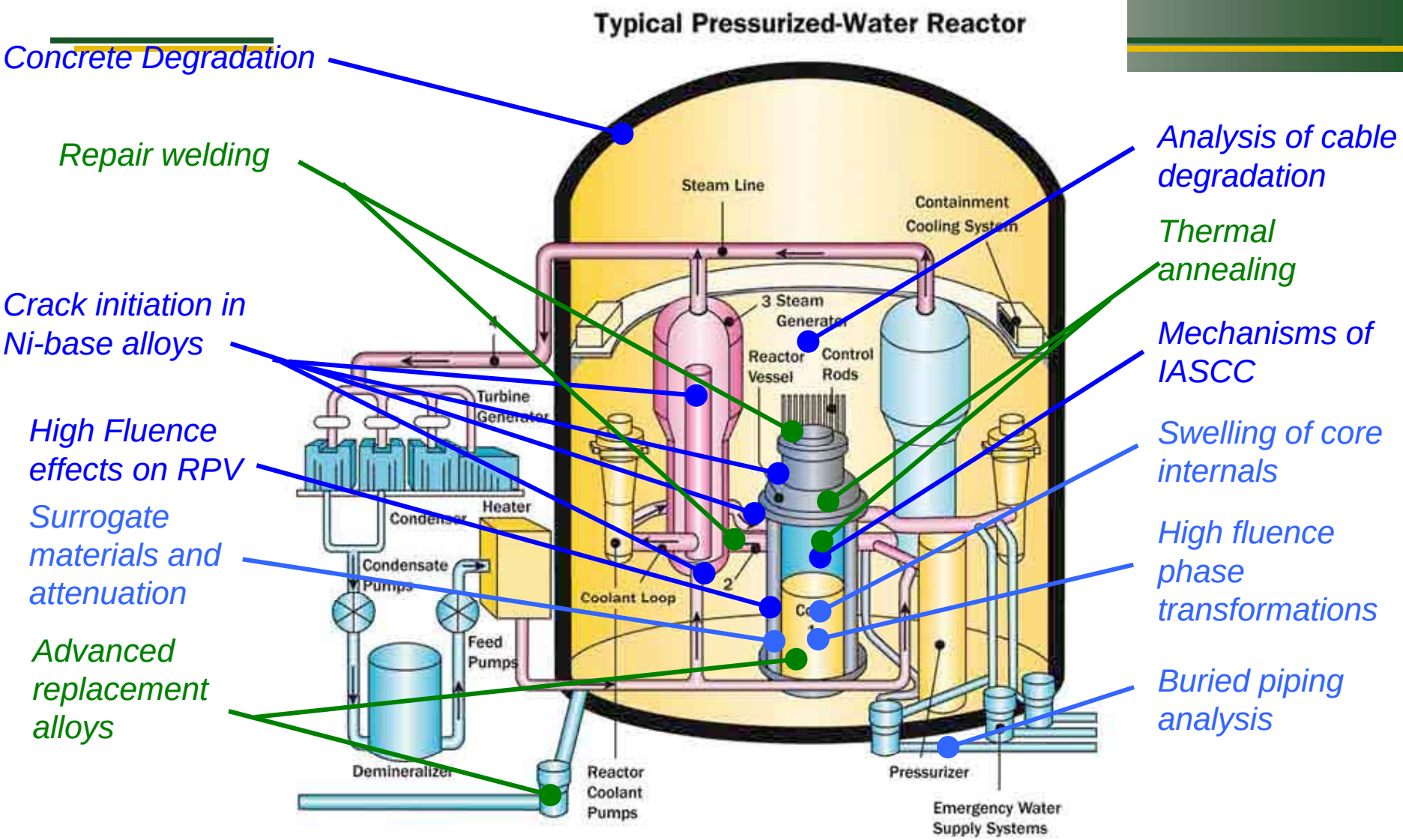


More directly, the LWRS Materials research tasks achieve two goals

- **Understanding and predictive capability for degradation of key components and materials.**
  - Mechanistic understanding
  - Predictive modeling
  - High quality data

- **Providing alternative technologies and methods to overcome degradation during extended operation**
  - Mitigation strategies
  - Alternative materials

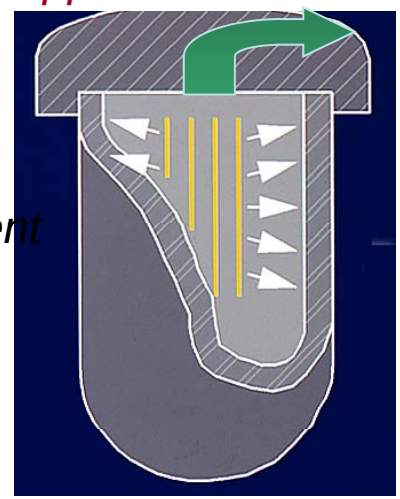
LWRS Materials Aging and Degradation research

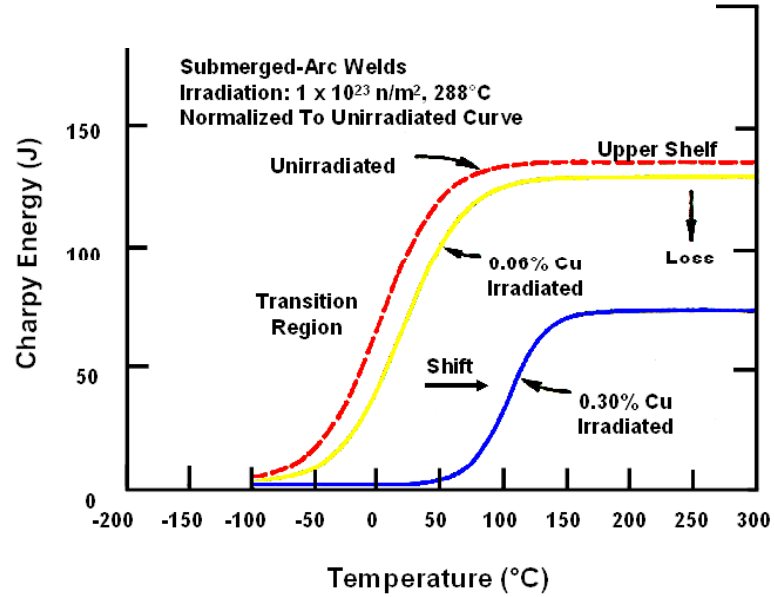


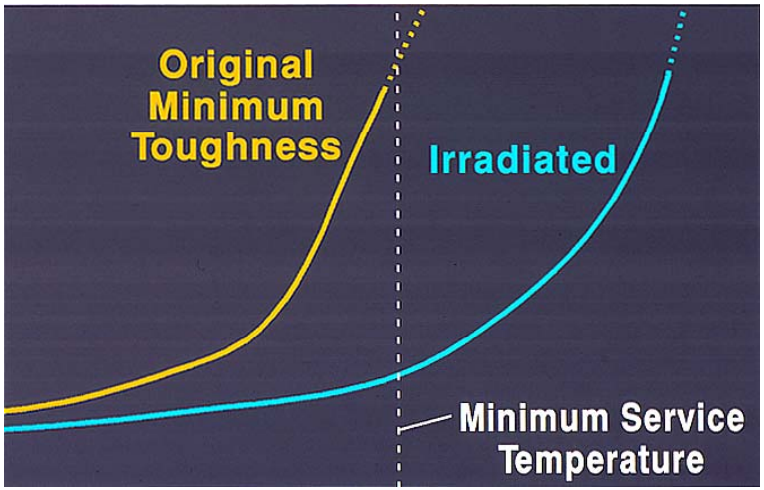
Reactor Vessel Integrity Assessments Must Account for Potential Degrading Effects of Neutron Irradiation

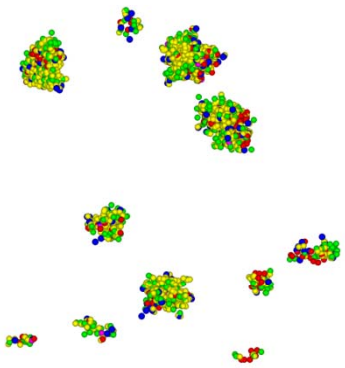
Irradiation Causes Ductile/Brittle Transition Temperature Shift and Upper Shelf Energy Loss — Copper Increases The Effect

Neutron Embrittlement of RPV







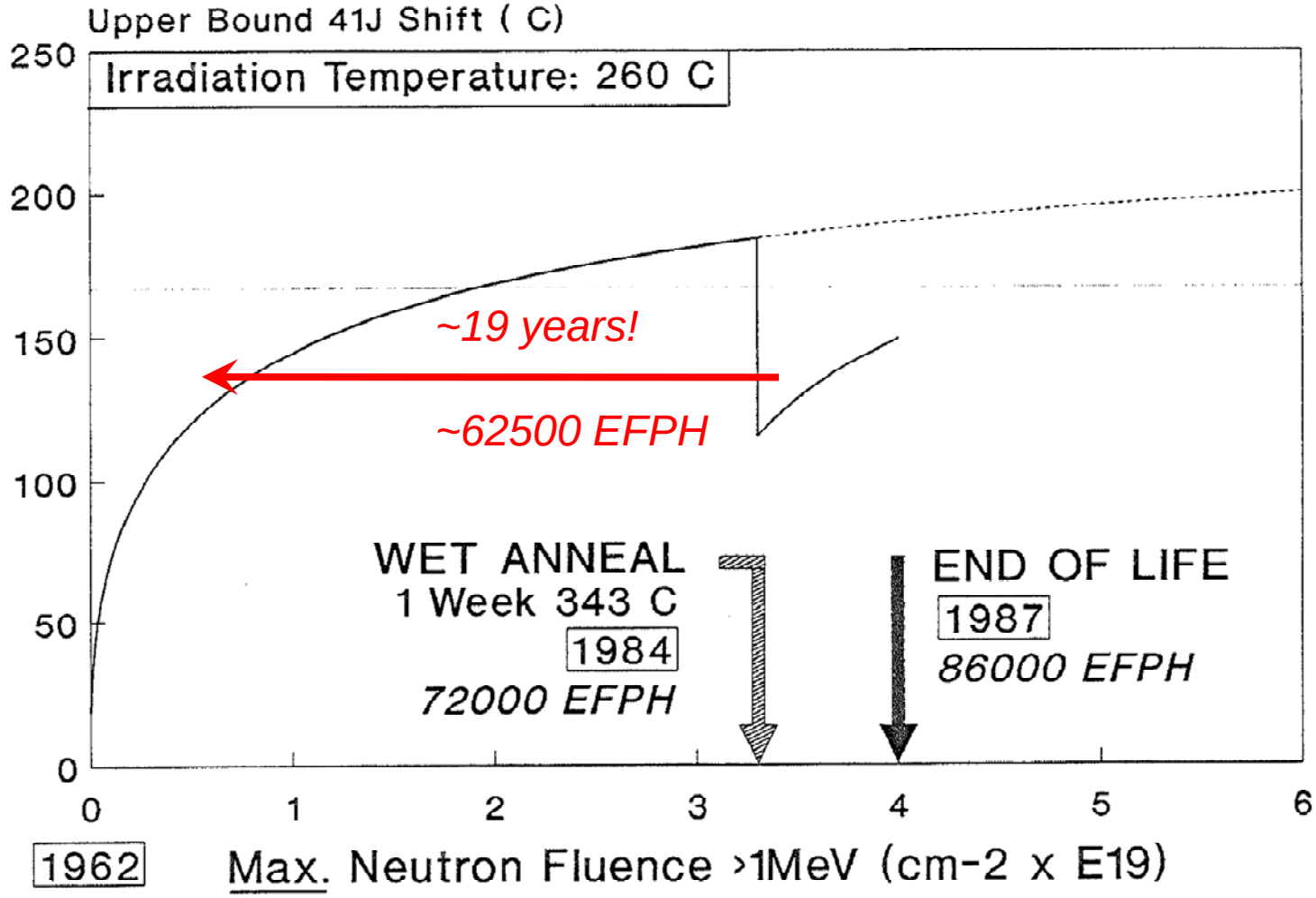


Precipitates ~2nm in diameter

Irradiated Microstructures: Precipitates and Matrix Damage

Thermal annealing has been performed on operating reactors around the world

Belgian BR3, Wet annealed at 343 ℃ for 168 hours



Source: R. Nanstad

Annealing of RPV's has been demonstrated world-wide

FIFTEEN (15) COMMERCIAL PWR VESSELS HAVE BEEN THERMALLY ANNEALED

NPP	UNIT	ANNEALING YEAR	CLADDING	ANNEALING BY
BR	3	1984	YES	BELGIAN
NOVOVORONEZH	3	1987	NO	RUSSIAN
ARMENIA	1	1988	NO	RUSSIAN
NORD†	1	1988	NO	RUSSIAN
KOLA	1	1989	NO	RUSSIAN
KOLA	2	1989	NO	RUSSIAN
KOZLODUY	1	1989	NO	RUSSIAN
KOZLODUY	3	1989	YES	RUSSIAN
NORD†	2	1990	NO	RUSSIAN
NORD	3	1990	YES	RUSSIAN
NOVOVORONEZH†*	3	1991	NO	RUSSIAN
NOVOVORONEZH†	4	1991	NO	RUSSIAN
KOZLODUY†	2	1992	NO	RUSSIAN
BOHUNICE	1	1993	YES	CZECH
BOHUNICE	2	1993	YES	CZECH

† Material Removed From Inner Surface of RPV for Examination

* Second Annealing

Source: R. Nanstad

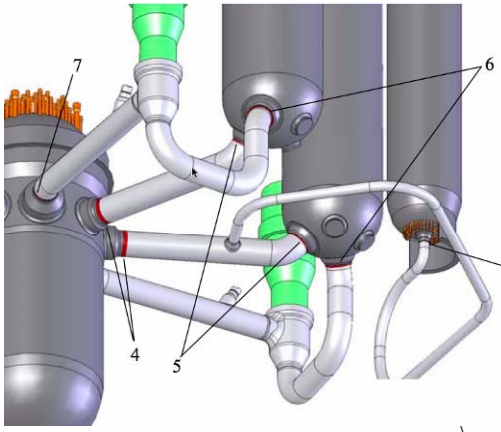
RPV annealing has also been demonstrated in the United States

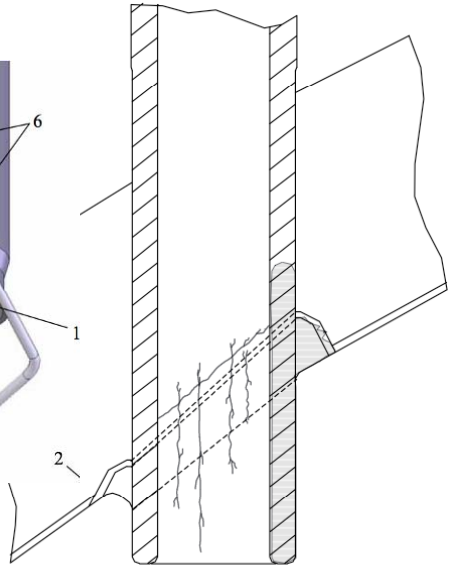
- In 1996, the joint DOE/industry Annealing Demonstration Project was performed at Marble Hill (Indiana)
- An independent panel found that "Successful completion of the ADP has demonstrated that functional requirements for in-place annealing of a U.S. RPV can be met using existing equipment and procedures."
- Title 10, U.S. Code of Federal Regulations, Part 50 specifies thermal annealing as a method for recovering the fracture toughness and refers to Regulatory Guide 1.162 (RG 1.162)
- Despite the technical demonstrations, this methodology has not been adopted or implemented to date.
- Several key technical, political, and operational issues must be resolved.

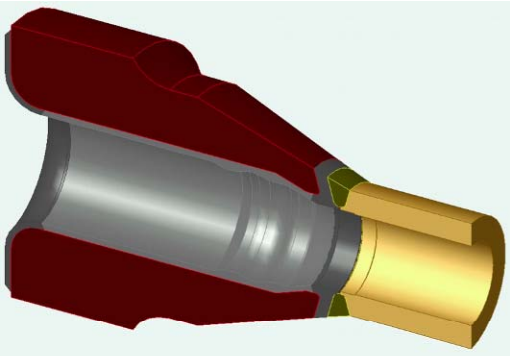
Source: R. Nanstad

Weld SCC is identified as one of key degradation modes in LWR's

- **May compromise functionality of the safety systems**
- **A recurring problem since the mid 1980s**
  - Three mile Island
  - 2000 VC summer, Ringhals 3 & 4
  - 2002 Davis-Besse, CRDM
  - 2003 Tsuruga (Japan)
  - 2005 Calvert Cliffs
  - 2006 Wolf Creek
- **SCC is driven by the high-tensile residual stress and microstructure changes in the weld region**
- **Current WRS models are far from adequate**







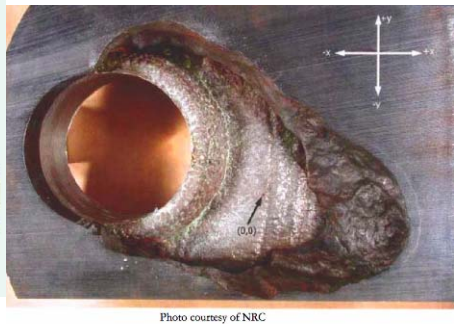
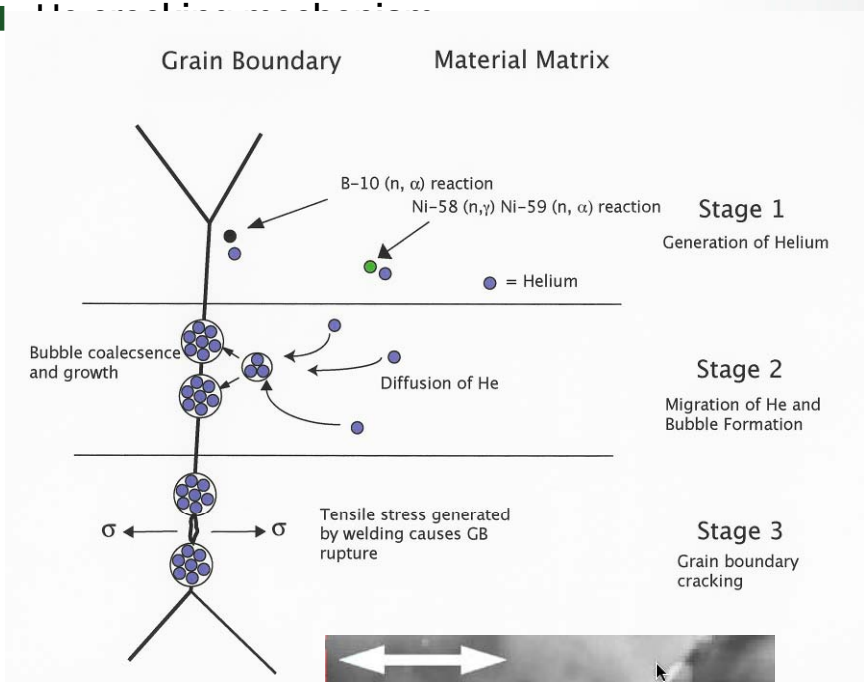
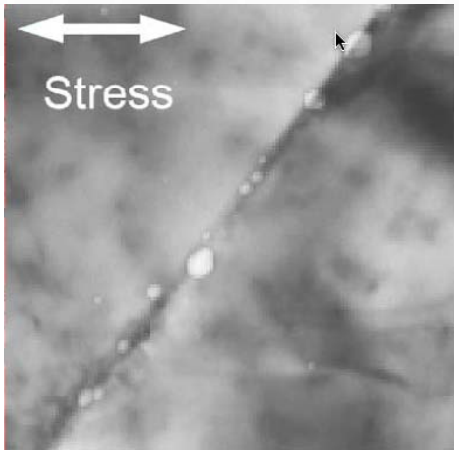


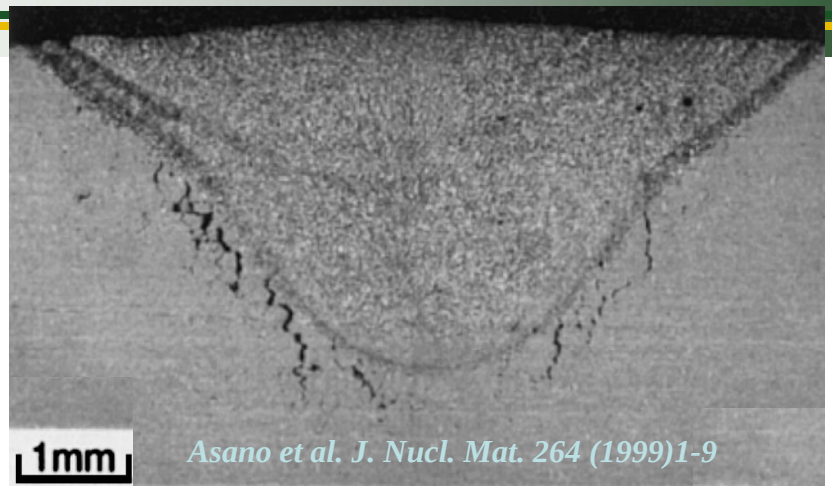
Photo courtesy of NRC

**** Expert Panel Report on Proactive Materials Degradation Assessment US NRC NUREG/CR-6923, 2007***

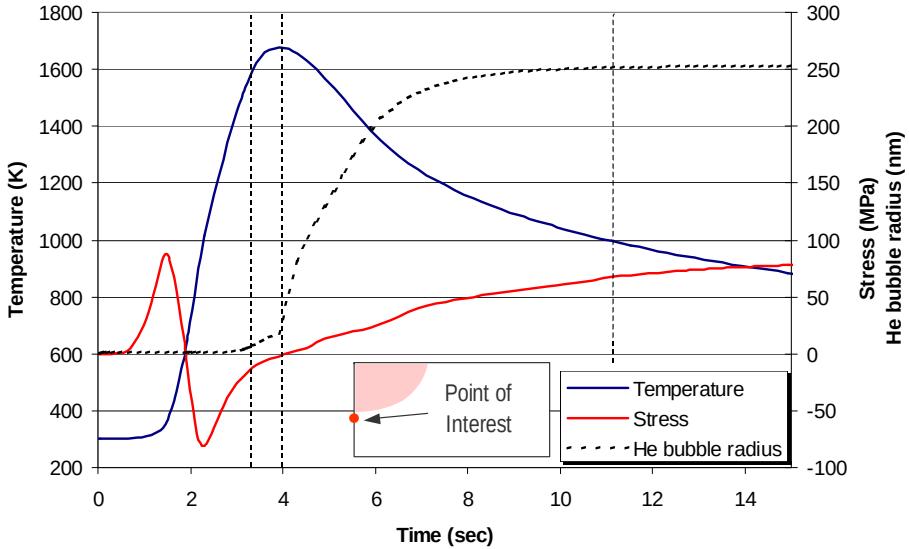
Weld repair of irradiated internals - helium induced degradation & cracking





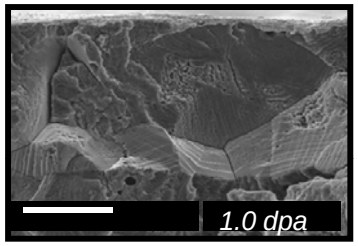
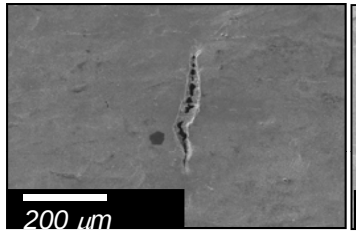
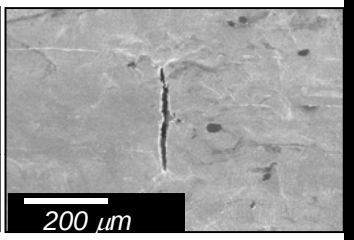
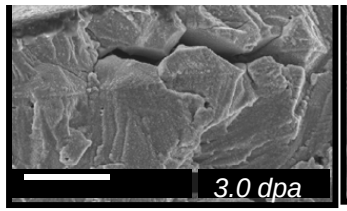
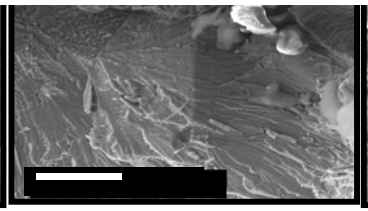
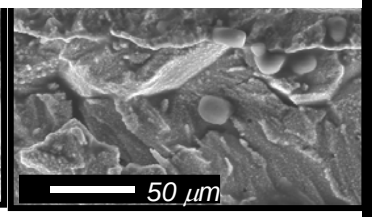
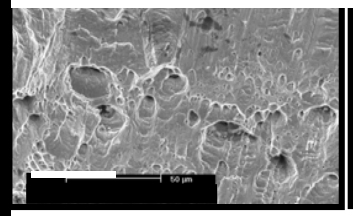
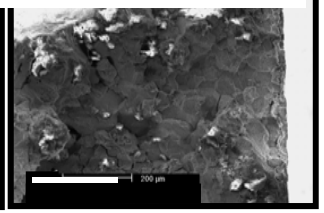


Asano et al. J. Nucl. Mat. 264 (1999)1-9



Source: Z. Feng

Limited post-irradiation annealing studies have also been successful in reducing IASCC in stainless steels

	As-Irrad.	400ºC/45 min.	450ºC/45 min.	500ºC/45 min.	600ºC/90 min.
1.0 dpa				No cracks observed	No cracks observed
2.5 dpa					

#IG cracks:	7	3	7	0	0
% As Irrad. IG Remain:	100 %	54%	62%	0%	0%

Source: J. Busby

Materials Aging and Degradation Summary

- **The DOE LWRS R&D program has initiated a materials research effort to help provide fundamental and mechanistic knowledge to support extended reactor service.**
  - IASCC
  - RPV issues
  - Concrete
  - Cabling
  - Ni-base alloys
  - Weldments
- **Future work may include other areas of research**
  - Irradiation-effects on internals
  - Buried piping evaluation
- **Mitigation strategies such as post-irradiation annealing, weld repair, or chemistry concepts are of particular interest**

Discussion?

LWRS

Light Water Reactor Sustainability