LWRS

Light Water Reactor Sustainability

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Light Water Reactor Sustainability: Materials Aging and Degradation

Life Beyond 60 Workshop

Jeremy Busby, ORNL

February 22-24, 2011

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

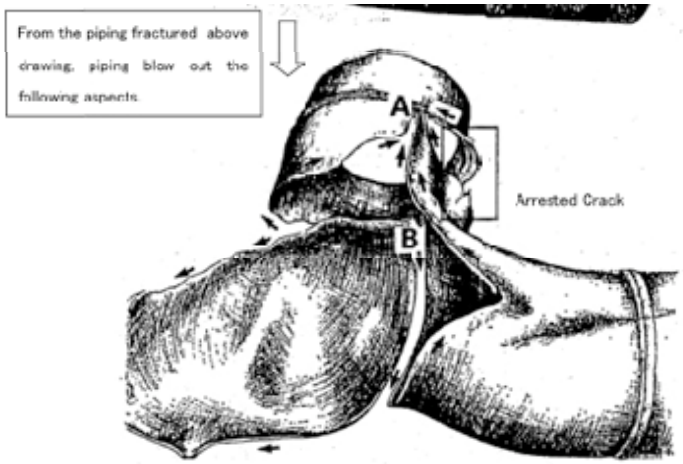
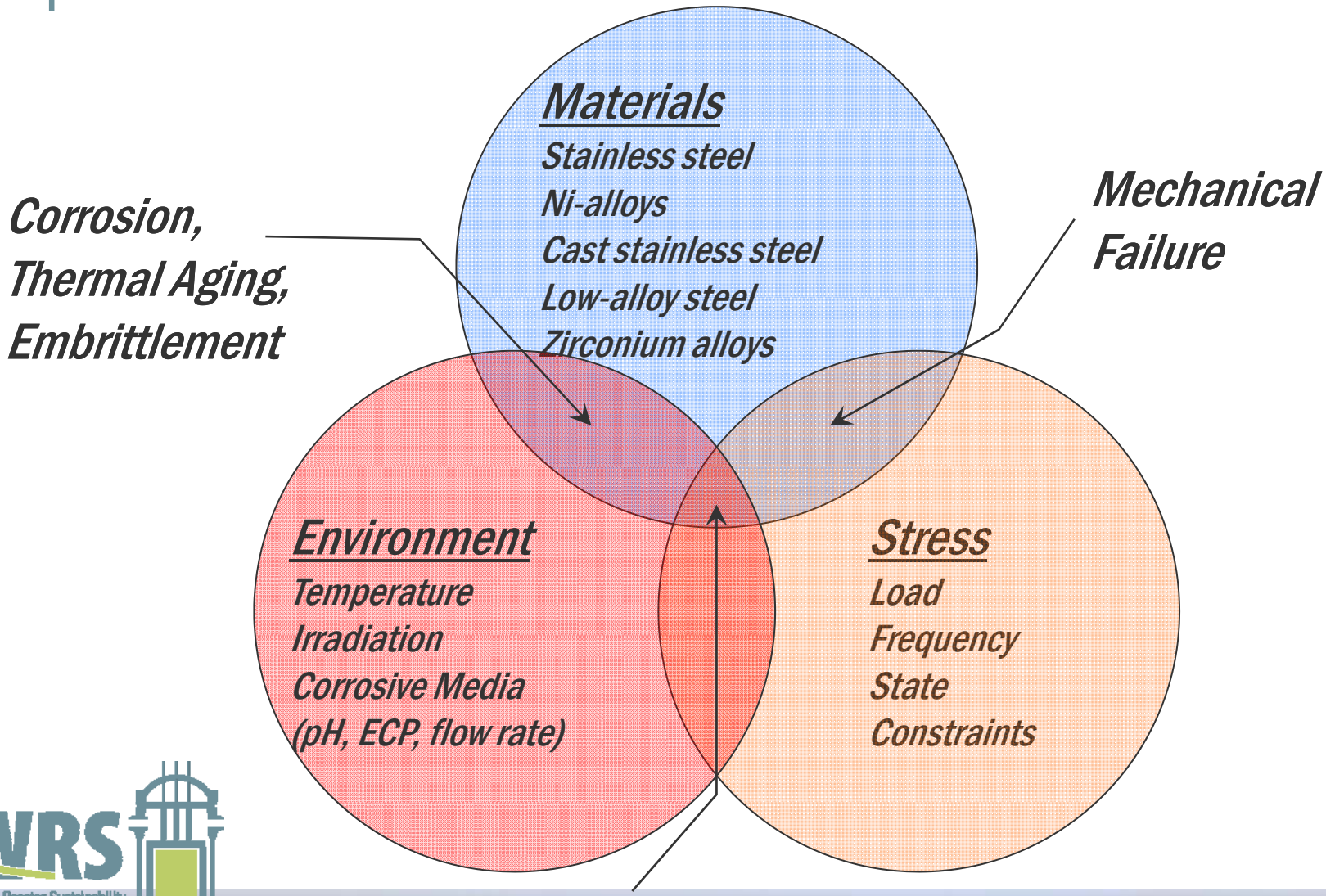


Fig.3 Detail Drawing of the Breaking Portion

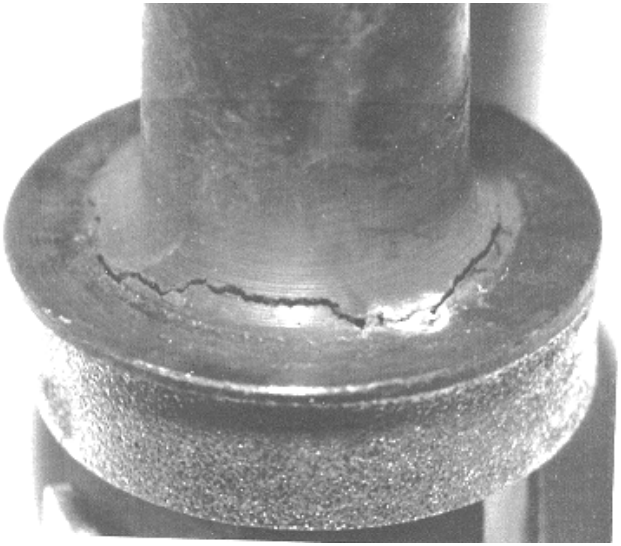
Materials aging and degradation in nuclear reactor components and systems is complex



Stress-Corrosion Cracking

Extension of service life may cause new challenges for materials service

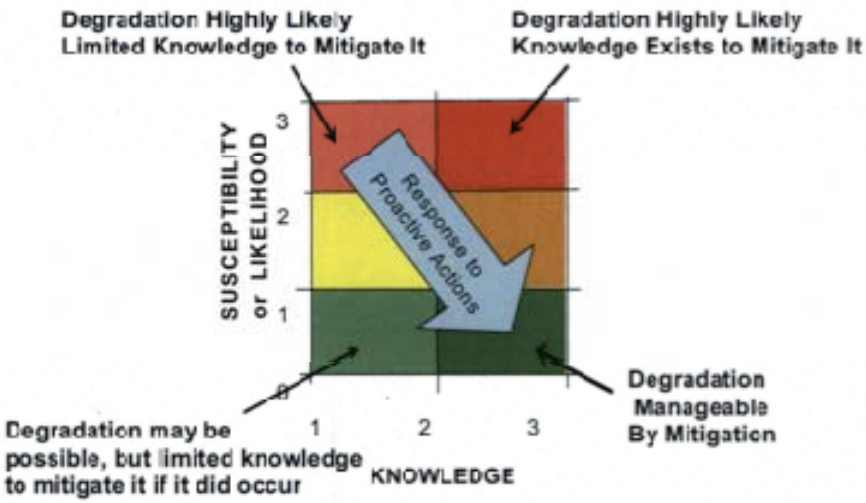
- Increased lifetime leads to increased exposures
  - Time at temperature
  - Stress
  - Coolant
  - Neutrons
- Extending reactor life to 40, 60 years or beyond will likely increase susceptibility and severity of known forms of degradation
- New mechanisms of materials degradation are possible
- The motivation of the Materials Aging and Degradation Pathway is to provide improved understanding of degradation under extended service and provide alternative mitigation strategies.



LWRS
Light Water Reactor Sustainability

In addition to other research for extended service, research must also identify other or new topics before they become life-limiting

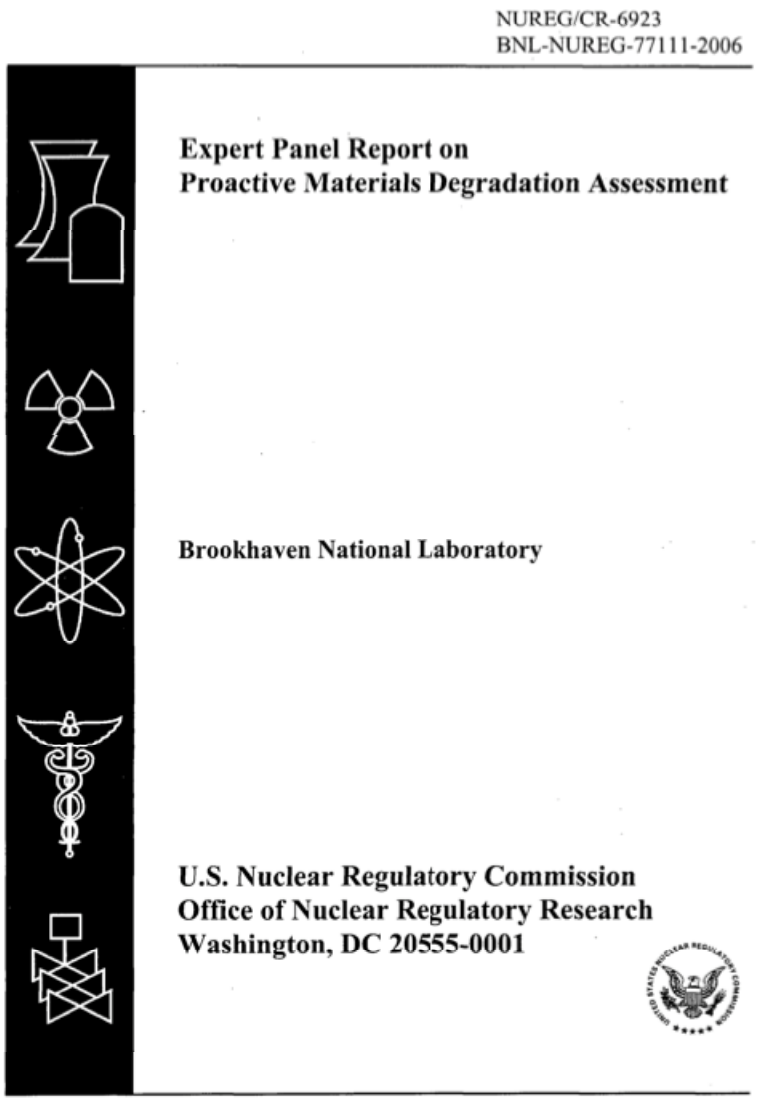
- "Knowing the unknowns" is a difficult problem that must be addressed.
- This is a particularly difficult issue for such a complex and varied material/environment system.
- An organized PMDA approach is being employed.
- Together with the USNRC, the LWRS program is working to expand the initial PMDA activity (*NUREG 6923)* to encompass broader systems and longer lifetimes
  - Core internals and primary piping
  - Pressure Vessel
  - Concrete
  - Cabling



***P**roactive **M**aterials **D**egradation **A**ssessment Matrix*

The US NRC and LWRS are both supporting the EPMDA

- Both sides are contributing funding in FY10/FY11
- *NUREG 6923* is being expanded beyond initial scope
  - *Longer lifetimes*
  - *Additional systems*
- Same PIRT process and expert panels are being employed.
- Product is complementary to EPRI's MDM


NUREG/CR-6923
BNL-NUREG-77111-2006

Expert Panel Report on
Proactive Materials Degradation Assessment

Brookhaven National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

Panelists have a diverse set of perspectives and experiences

Core Internals and Piping		RPV	Concrete	Cables
J. Busby (ORNL)	S. Bruemmer (PNNL)	R. Nanstad (ORNL)	D. Naus (ORNL)	R. Bernstein (SNL)
A. Hull (NRC)	G. Carpenter (NRC)	M. Kirk (NRC)	H. Graves (NRC)	S. Ray (NRC)
R. Dyle (EPRI)	K. Arioka (INSS)	B. Server (Consult)	J. Wall (EPRI)	G. Toman (EPRI)
P. Andresen (GE)	R. Staehle (Consult)	B. Odette (UCSB)	J. Rashid (Anatech)	K. Simmons (PNNL)
K. Gott (SSI)	G. Was (UM)	N. Soneda (CRIEPI)	Y. Le Pape (EdF)	K. Gillen (Consult)
P. Ford (Consult)	M. Wright (AECL)	B. Burgos (Westinghouse)	V. Sauma (UC)	

LWRS
Light Water Reactor Sustainability

Research tasks within the Materials Aging and Degradation Pathway seek to inform relicensing decisions and processes

- To support the LWRS R&D goals, this effort will:
  - Develop the scientific knowledge basis for understanding and predicting changes to key materials as a function of their use and the environment in nuclear power plants. Support development of methodologies used in accurately predicting lifetime performance of SSCs during extended plant operations.
- Research supports this broad goal in several areas
  - Understand known materials degradation phenomena that are expected to grow more severe with extended service
  - Understand materials degradation phenomena that are expected to occur based on current knowledge, but which have not yet been observed.
  - Enhance the current state of knowledge on materials degradation phenomena and inform life extension decision processes or improved safety margins for new plants and new designs.
  - Support advanced technologies to mitigate or repair materials aging and degradation phenomena or improve performance in new plants and designs

LWRS
Light Water Reactor Sustainability

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

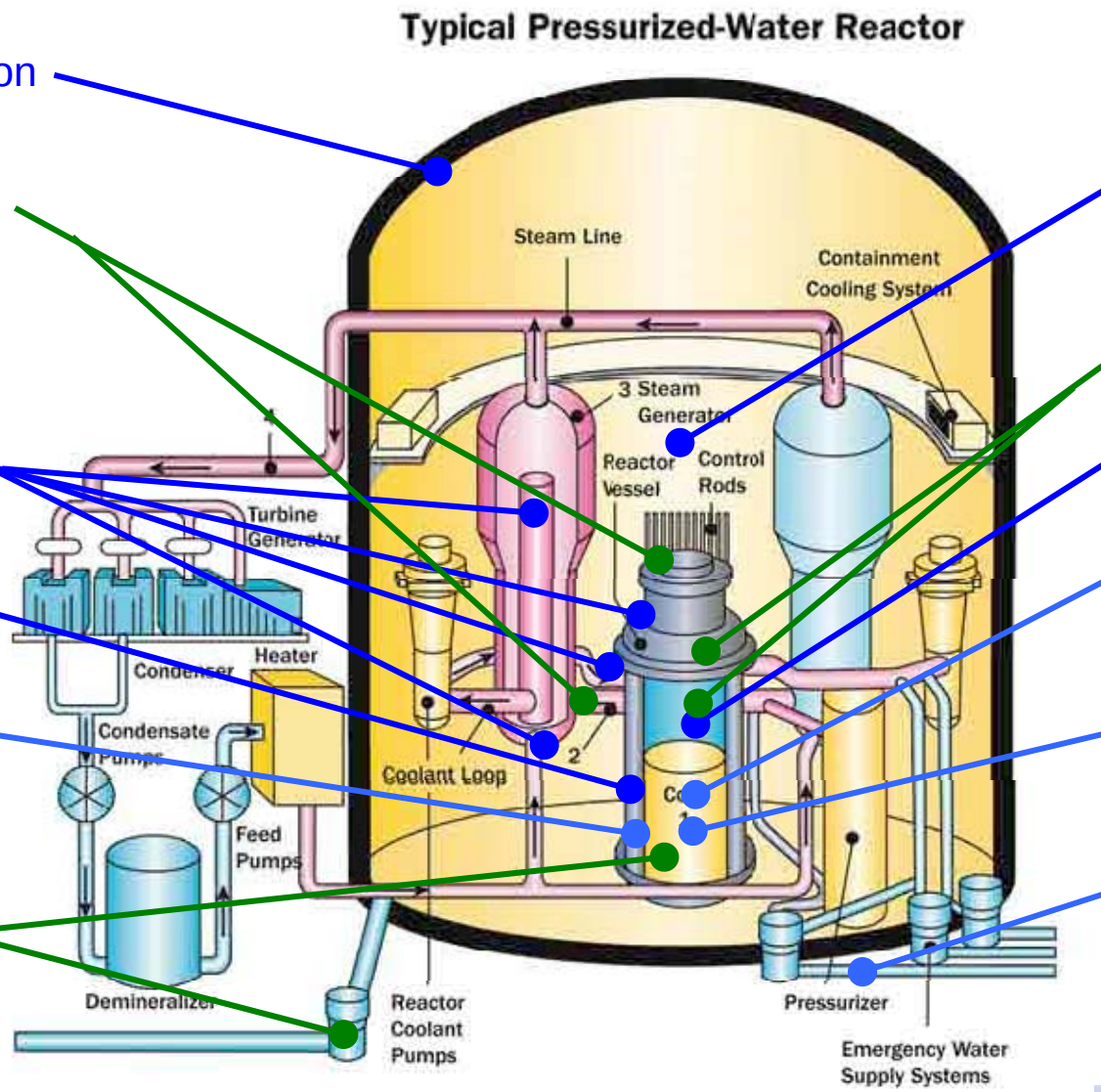
Near term support

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

Long-term alternatives
High-risk, high-reward

LWRS
Light Water Reactor Sustainability

LWRS Materials Aging and Degradation research encompasses entire plant



Concrete Degradation

Repair welding

Crack initiation in Ni-base alloys

High Fluence effects on RPV

Surrogate materials and attenuation

Advanced replacement alloys

Analysis of cable degradation

Thermal annealing

Mechanisms of IASCC

Swelling of core internals

High fluence phase transformations

Buried piping analysis

LWRS
Light Water Reactor Sustainability

Key MAaD deliverables have been oriented to support decision processes in coming years

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
IASCC			Procure commer. Materials		Complete mechanistic studies	Initiate Predictive modeling		Benchmark		Predictive model
--EPRI			IASCC knoweldge base		Parametric correlations		Crack growth model		IASCC resistant materials	
EASCC			Characterization of pre. States		Complete mechanistic testing			Deliver predictive model		
--EPRI			Knowledge Database				Crack Growth Model	Mitigation Strategies		Crack initiation model
RPV		Acquire Palisades samples	Analysis of Palisades	PIE of ATR irradiations		Validated model of TTS				
--EPRI					Revision trends to embr. model					
Welding					Hybrid welding demo	Validation of welds on irrad. mater			Transfer of tech to industry	
--EPRI				Models for Hybrid welds		Validation of hybrid welds				

Light Water Reactor Sustainability

Buy it and forget may not be the most economical option for sustained operation

- Improvements in knowledge levels, management practices, and new materials are significant.
- Recent experience is that manufacturing defects and processes may be primary cause in replacement components.
  - Driving new precursors and possibly new modes of degradation.
  - Removing defects can be costly.
- Alternatives to component replacement may provide greater economical impact and efficiency
  - Welding of cracked components
  - Annealing of reactor pressure vessels
  - Annealing of core internals

LWRS
Light Water Reactor Sustainability

The Materials Aging and Degradation is a national program and must be inclusive of the leading experts and research around the world

- In order to be effective, materials support for LWRS R&D must be a broad-based program.
  - Provides a more comprehensive experimental capability.
  - Utilizes experts and facilities from across the nation
    - National laboratories
    - Universities
    - EPRI
    - NRC
    - Vendors (e.g. Areva, Westinghouse, and GE)
    - Utilities (directly or via EPRI)
  - International expertise should also be engaged to the fullest

Idaho National Laboratory

Oak Ridge National Laboratory
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Pacific Northwest NATIONAL LABORATORY

Sandia National Laboratories

EPRI ELECTRIC POWER RESEARCH INSTITUTE

MICHIGAN

UCSB

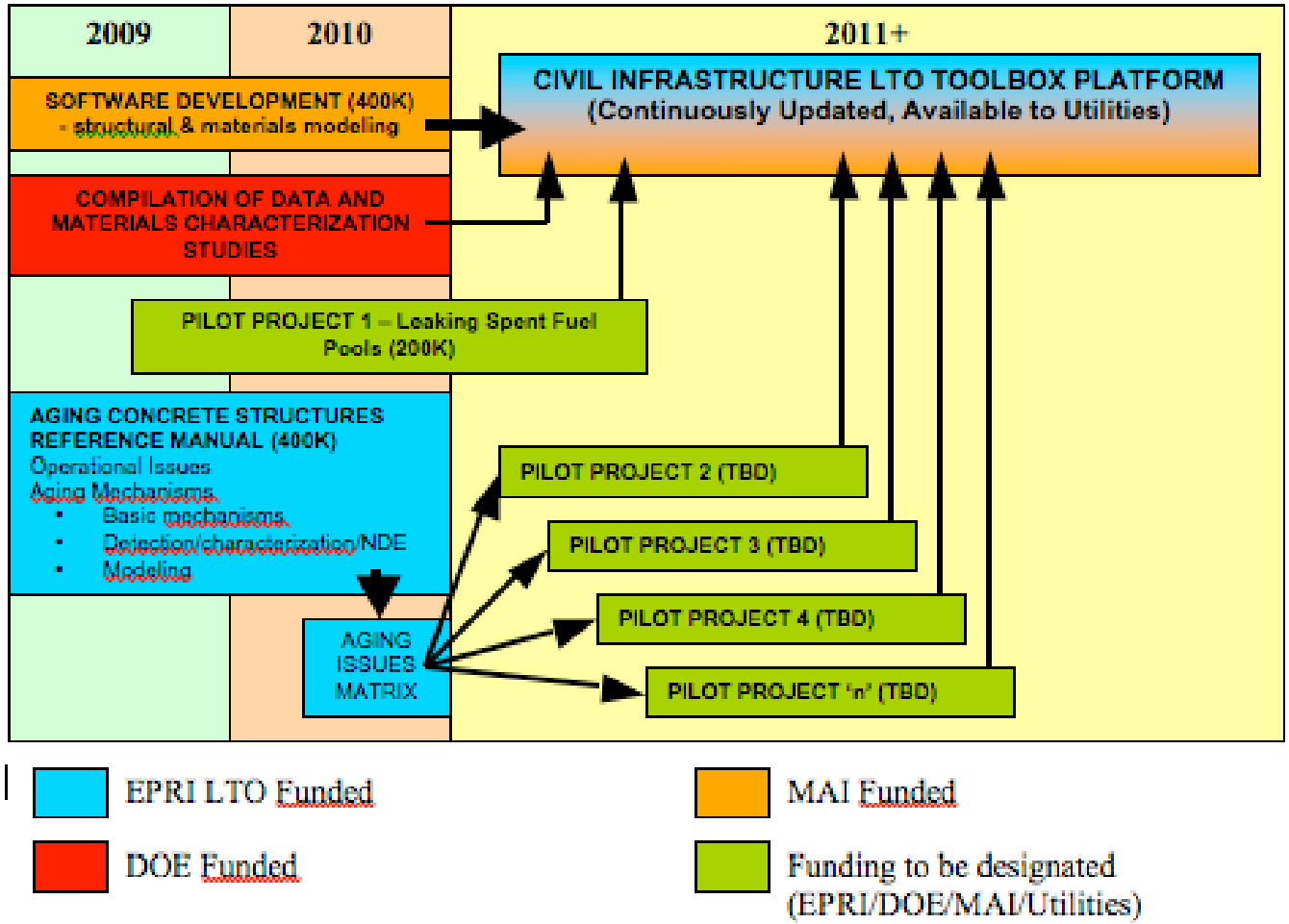
LWRS Light Water Reactor Sustainability

Industry and International Collaboration is a key desire of this pathway

- The LWRS Program has been designed to facilitate industry and government (DOE) decisions on long-term LWR operations
- EPRI and NRC collaborations and integrations have been a positive part to the program.
- Partnerships with the Materials Aging Institute have been discussed and informally initiated in the evaluation of concrete.
- The IASCC task is retrieving specimens irradiated as part of an international cooperative group.
- The RPV task is using specimens irradiated in the BR-2 reactor as part of an international campaign.
- Discussions with the Halden Reactor Project have identified several key areas of potential collaboration.

LWRS
Light Water Reactor Sustainability

Concrete evaluations are now part of a collaborative effort with EPRI and MAI



The LWRS also has a unique opportunity to participate in extensive plant inspections

- In spring 2011, the Ginna PWR reach 41 years of service and will undergo maintenance and inspection
- The results of the inspection will be informative to many tasks and may give key insights into MDM and PMDA activities
- Within MAaD and LWRS, discussions on scope continue.
- Areas of interest include
  - Acquiring baffle bolts
  - Concrete inspections
  - Cable surveillance
  - RPV coupon analysis.

LWRS
Light Water Reactor Sustainability

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
  - Irradiation effects at high fluence (swelling and phase transformations)
  - RPV issues
  - Concrete
  - Cabling
  - Ni-base alloys
  - Weldments
- **Future work may include other areas of research**
  - High fluence IASCC
  - Buried piping evaluation
  - Environmental fatigue
- **Mitigation strategies such as post-irradiation annealing, weld repair, or chemistry concepts are of particular interest**

Discussion?

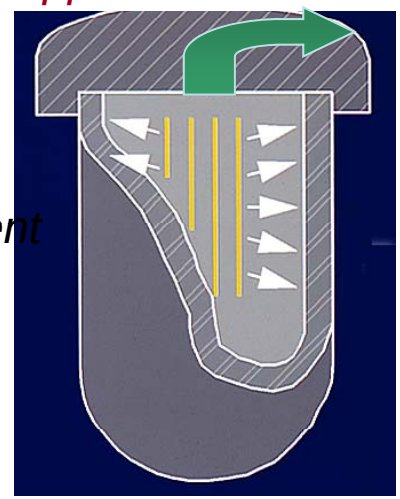
LWRS

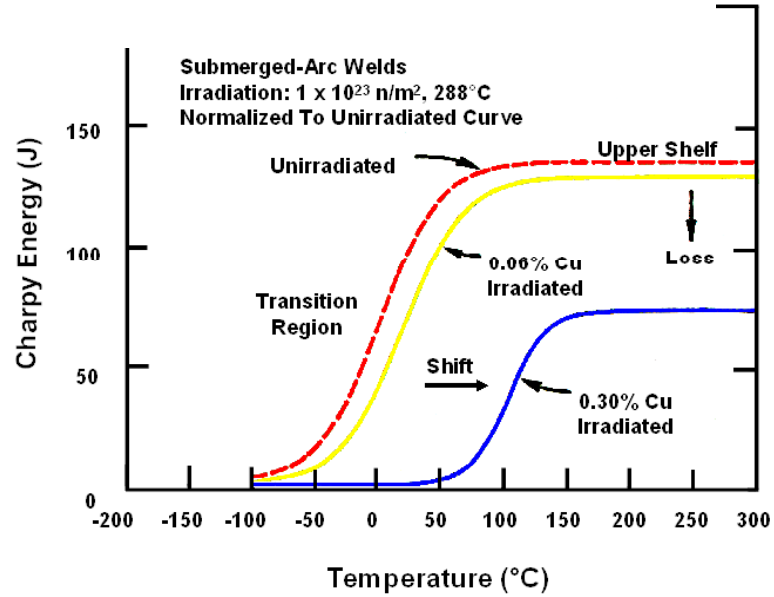
Light Water Reactor Sustainability

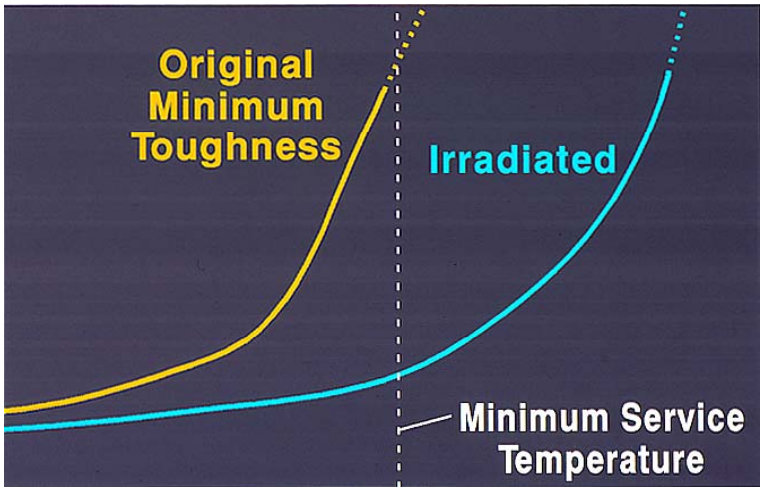
Reactor Vessel Integrity Assessments Must Account for Potential Degrading Effects of Neutron Irradiation

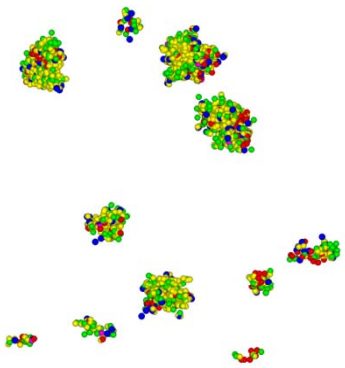
Irradiation Causes Ductile/Brittle Transition Temperature Shift and Upper Shelf Energy Loss — Copper Increases The Effect

Neutron Embrittlement of RPV







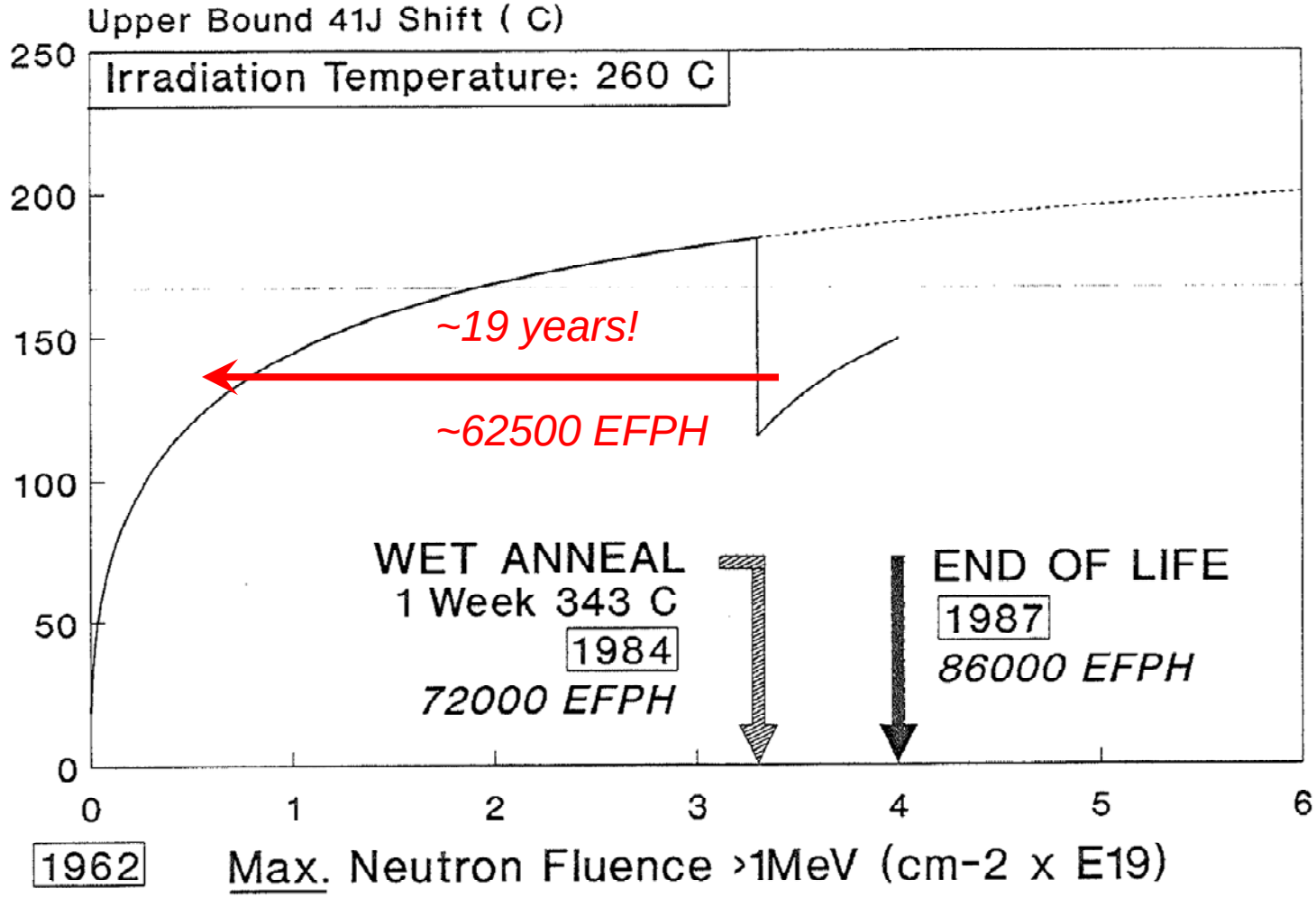


Precipitates ~2nm in diameter

Irradiated Microstructures: Precipitates and Matrix Damage

Thermal annealing has been performed on operating reactors around the world

Belgian BR3, Wet annealed at 343° C 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

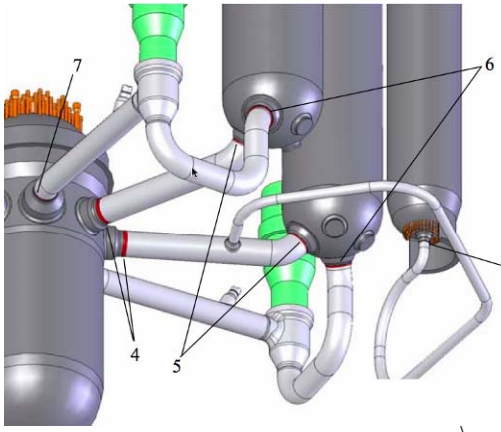
RPV annealing has also been demonstrated in the United States

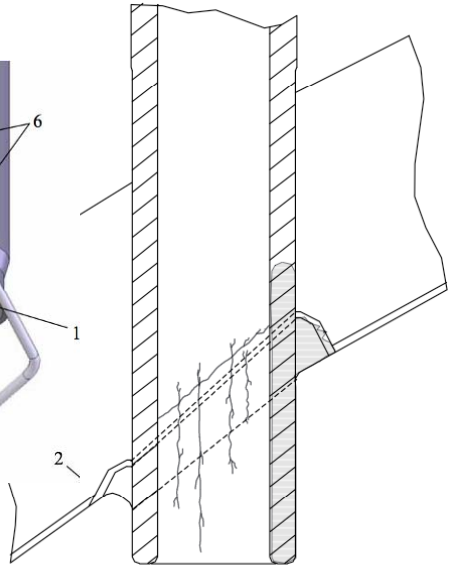
- In 1996, the joint DOE/industry Annealing Demonstration Project was performed at Marble Hill (Indiana)
- An independent panel found that "Successful completion of the ADP has demonstrated that functional requirements for in-place annealing of a U.S. RPV can be met using existing equipment and procedures."
- 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.

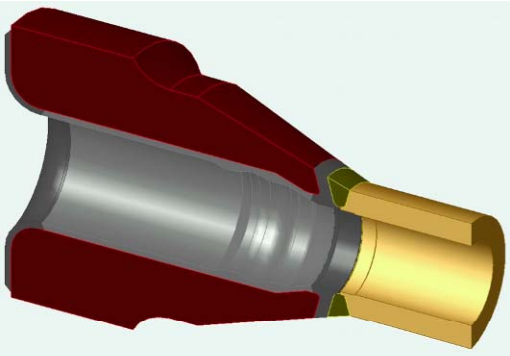
Source: R. Nanstad

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**







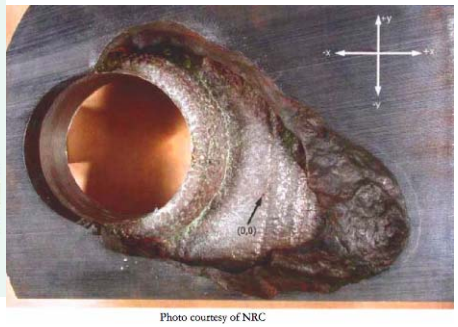
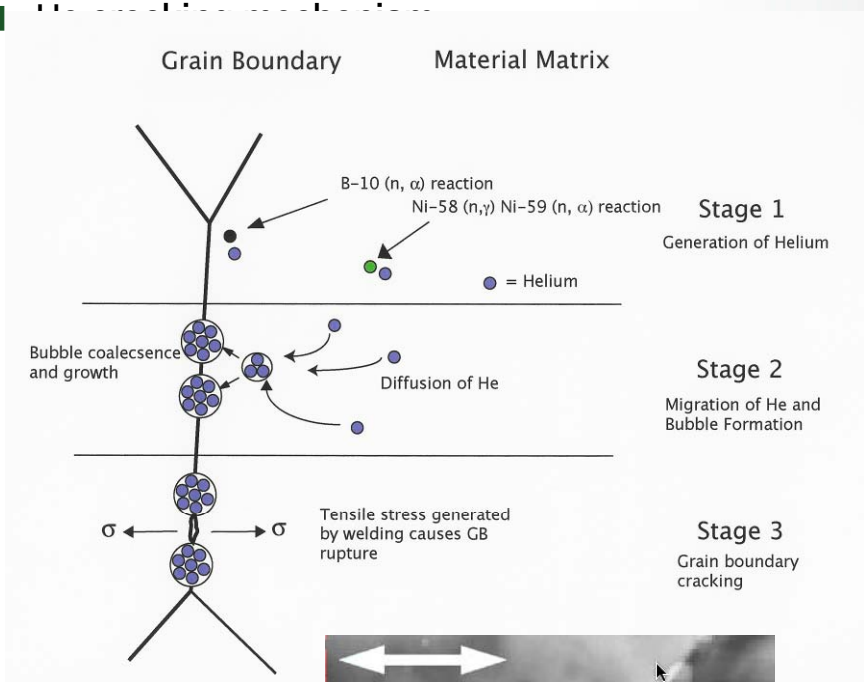
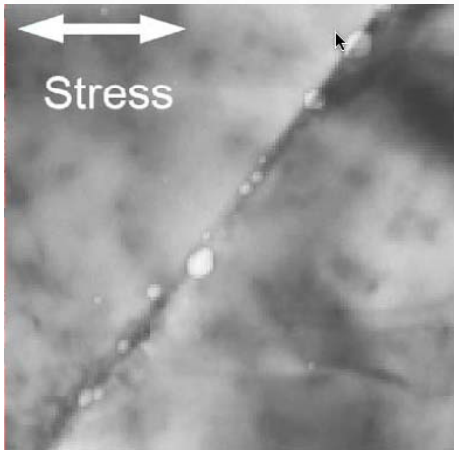


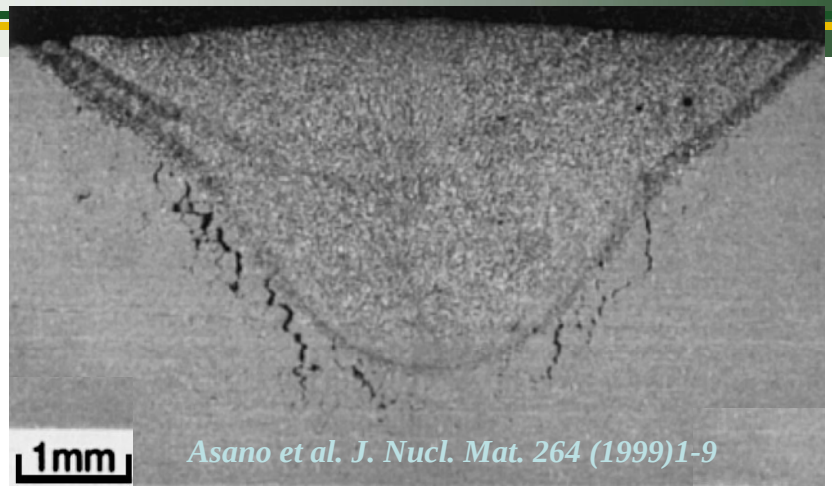
Photo courtesy of NRC

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

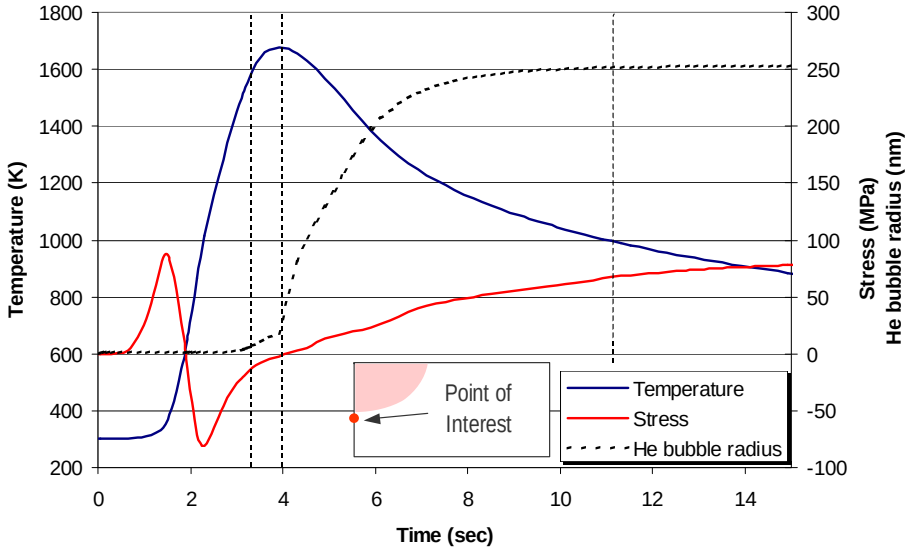
Weld repair of irradiated internals - helium induced degradation & cracking





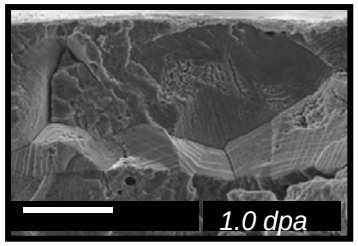
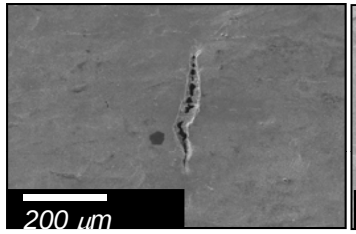
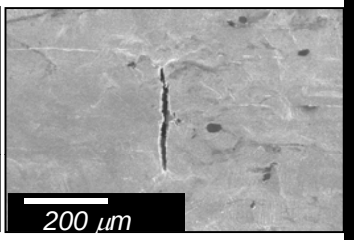
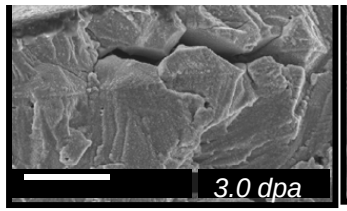
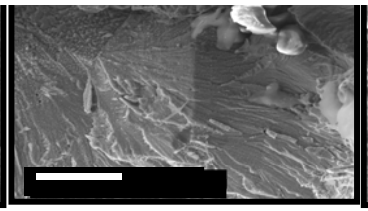
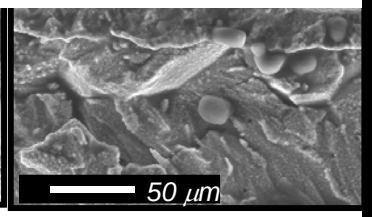
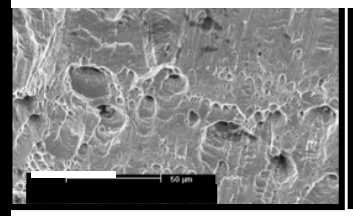
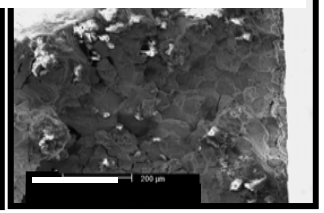


Asano et al. J. Nucl. Mat. 264 (1999)1-9



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