Potential materials issues to monitor for stainless steel reactor internals during extended plant life to 80-100 years*

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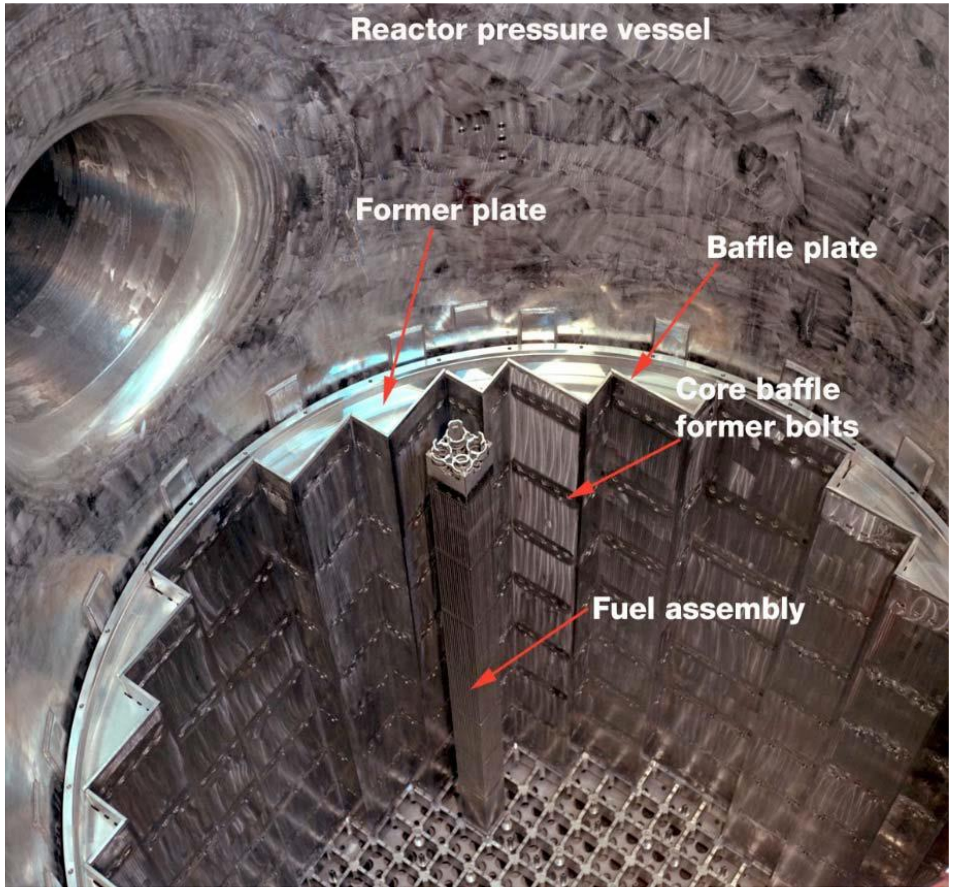
***Maximum dose of 200-250 dpa in PWRs, but much less in BWRs**

Background



Internal components of a Westinghouse design PWR

- Stainless steels (AISI 304, 316, 347, 321) comprise the majority of non-fuel structural components in Western design LWRs.
- The physical and mechanical properties, and also the dimensional stability of the steels, are degraded with continuing irradiation at elevated temperatures.
- Changes in these properties determine the safety or economic lifetime of individual core components.
- Proximity of the steel to the core determines the rate of degradation so that steels in PWRs receive higher dose rates than BWRs (water gap of 1-3 mm vs. several cm, respectively).
- First-order degradation processes have long been under active study and surveillance (embrittlement, cracking, corrosion).
- Concerns for extended lifetimes are

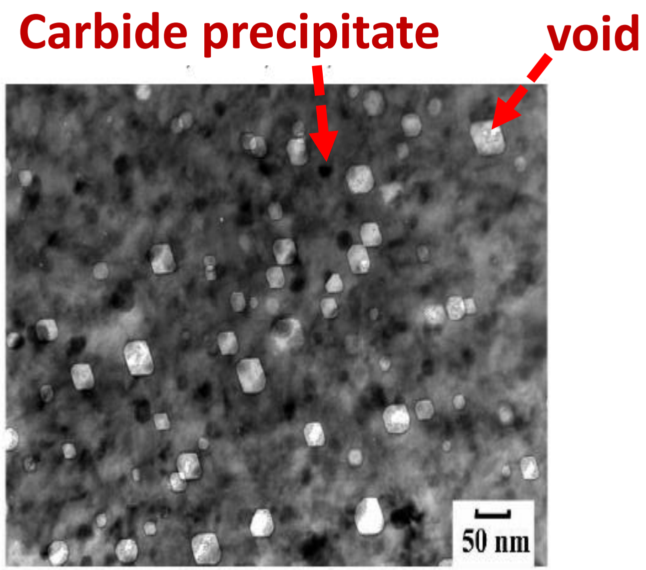
  second-order processes growing to first-order importance

  previously unidentified phenomena at higher exposure

  enhanced synergisms between various phenomena

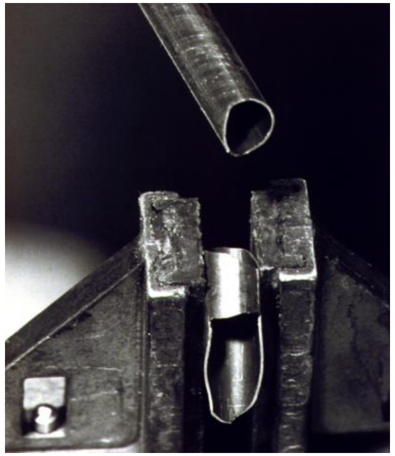
Previously identified second-order phenomena

- Phase instability and elemental redistribution, especially with respect to precipitation (carbides, gamma prime, G-phase)
- Development of magnetic nanofeatures (seeds for future phase instabilities?)
- Transmutation-induced helium (^{4}He) and hydrogen
- Storage of both transmutant and environmental hydrogen in helium bubbles ~600 appm He, ~2500 appm H after 18 years
- Impact of ^{4}He and perhaps H on repair welding

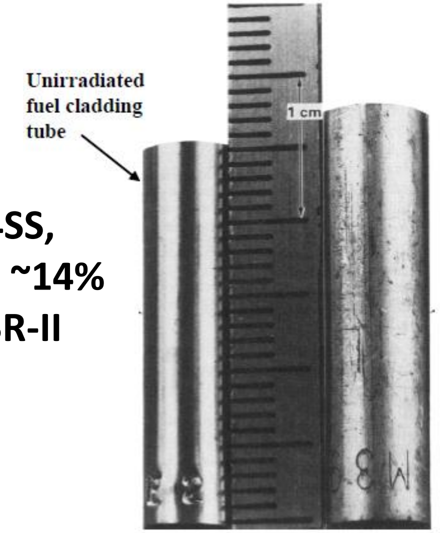


Annealed 304SS , 22 dpa, 380°C in EBR-II

- Irradiation creep
- Void swelling (6% design maximum)
- Void-induced embrittlement (>10%)



Annealed 304SS, 75 dpa, 400C, ~14% swelling in EBR-II

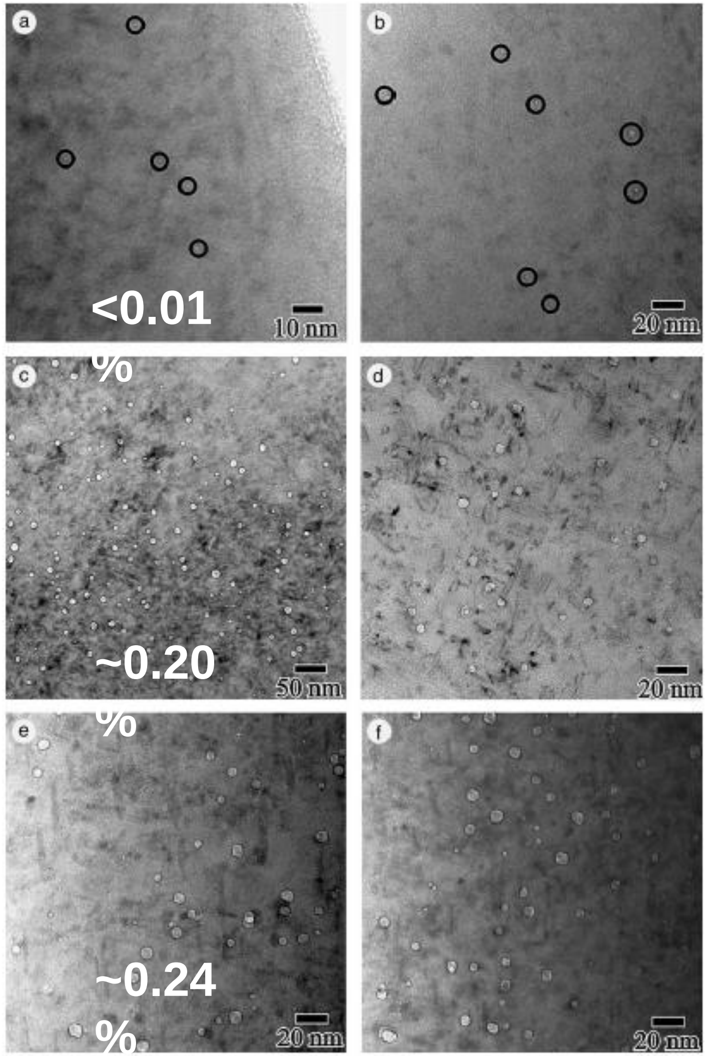


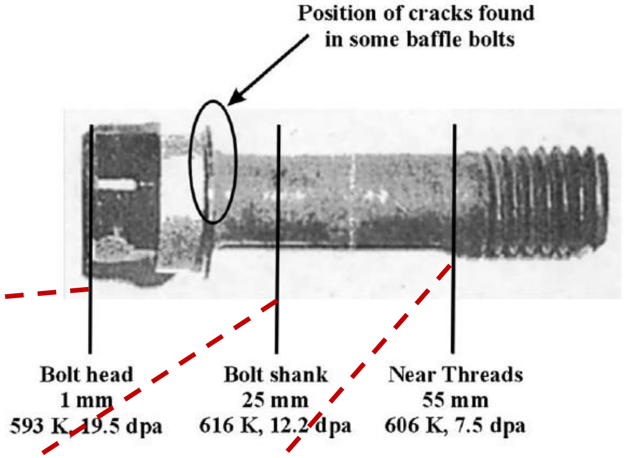
Cold-worked 316 80 dpa, 520°C in EBR-II producing a volume increase of ~30%

Emerging phenomena that require increased attention

- **Increasing tendency toward deformation-induced martensite**
- **Formation of iron-rich ferrite, especially on grain boundaries**
- **Both above may impact corrosion and cracking**
- **Increasing storage of hydrogen may affect cracking and martensite formation. It may also accelerate void swelling at some temperatures.**
- **Increasing impact of previously negligible solid transmutation products, especially loss of Mn and formation of V, thereby increasing ferrite and martensite formation.**
- **Impact of solid transmutation and radiation-induced segregation on phase instability and cracking/corrosion**
- **Out-of-core accumulation of ^{3}He from tritium absorption and decay with an impact on repair welding (20-50 appm recently measured)**

Gradient in thermal-to-fast neutron ratio along a 316 stainless steel PWR baffle bolt producing differences in void swelling and transmutation





T/F ratio varied from ~0.2 at the bolt head to ~0.4 at the near-threads position, producing a higher rate of transmutation per dpa at the lowest dpa rate.

Distance from bolt head, mm	dpa	Burnout loss of Mn
1	19.5	7.1%
25	12.2	5.9%
55	7.5	5.6%

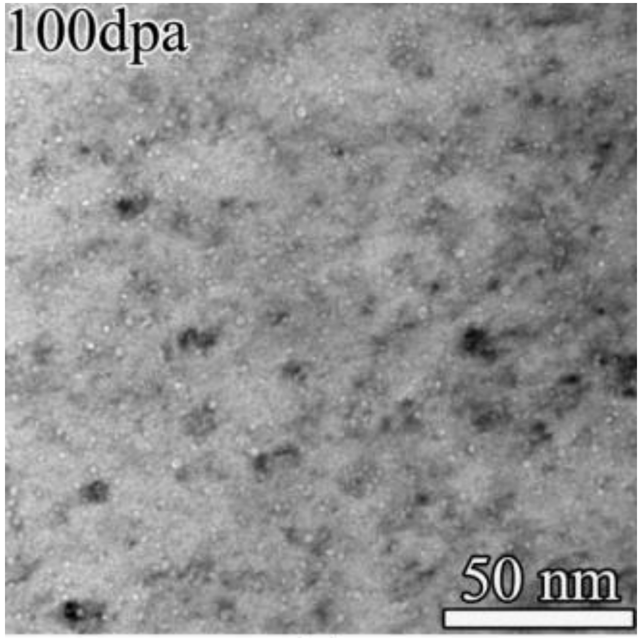
Position (mm)	^{1}H (appm)	^{4}He (appm)
1	493, 743	71
25	720, 1260, 3660, 3710	52.7
55	1840, 3740	48.8

Current status of understanding and predicting void swelling in PWR internals

- Swelling is a life-limiting phenomenon in fast reactors at higher temperatures. Will it be limiting in PWRs?
- Swelling exhibits an incubation period with duration determined by composition, processing and reactor variables, especially irradiation temperature.
- Post-incubation swelling rate in fast reactors is very high at ~1%/dpa.
- Most data at high exposure were generated in the EBR-II and FFTF fast reactors at much higher damage rates and temperatures >365-370°C, well above most of the PWR temperature range.
- Data from foreign fast reactors with lower inlet temperatures (DFR, BN-350, BOR-60, BN-600), indicates that below ~370°C the swelling rate falls to much lower values, especially at lower dpa rates.
- Very low swelling (<0.5%) has been observed to date in various examined PWR baffle bolts and flux thimble tubes.

- Major conclusion: swelling by itself is unlikely to be life-limiting in PWRs. Other synergisms with voids may contribute to life-limitation, however.

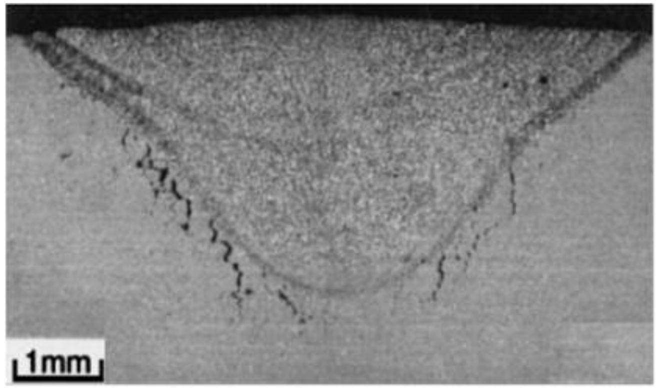
Song et al, JNM 541, 2020



Swelling <0.05% in a cold-worked 316 flux-thimble tube after 34 years in a PWR.
~1000 appm He was measured

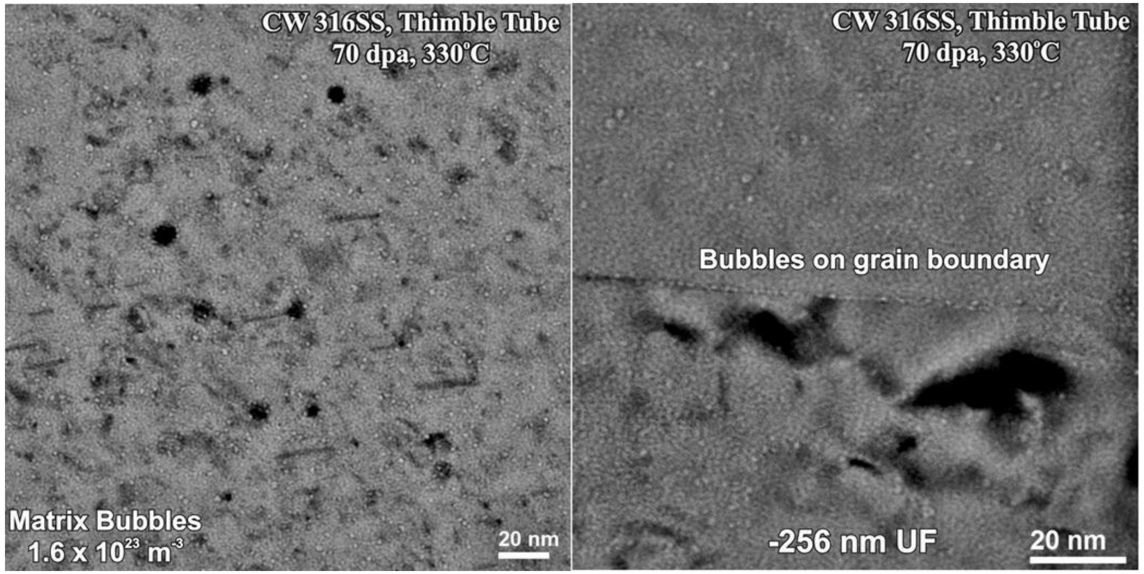
Helium-induced cracking during repair welding

Note: ^4He forms in-core but ^3He from ^3H accumulates out-of-core.



Annealed 304 SS from Japanese BWR

8.3 appm
~1 dpa



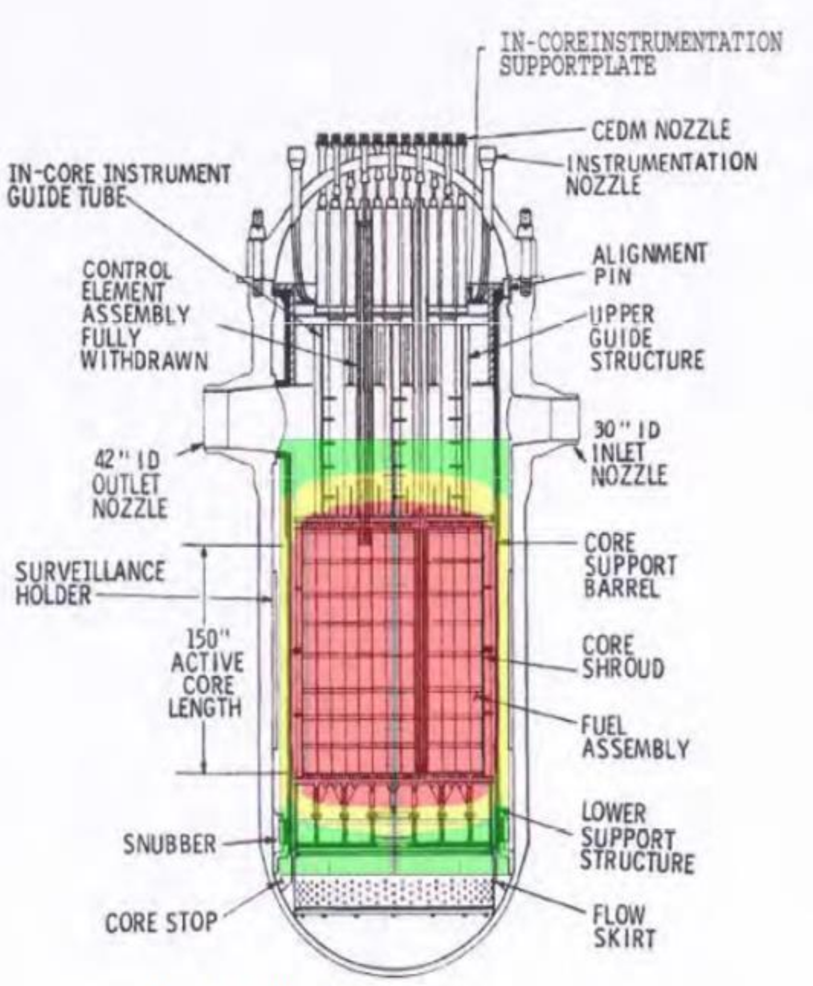
CW 316 SS flux-thimble tube

~600 appm He,
~2500 appm H

He concentration less than 0.1 appm
No heat input control required

He concentration greater than 0.1 appm and less than 10 appm
Heat input control required

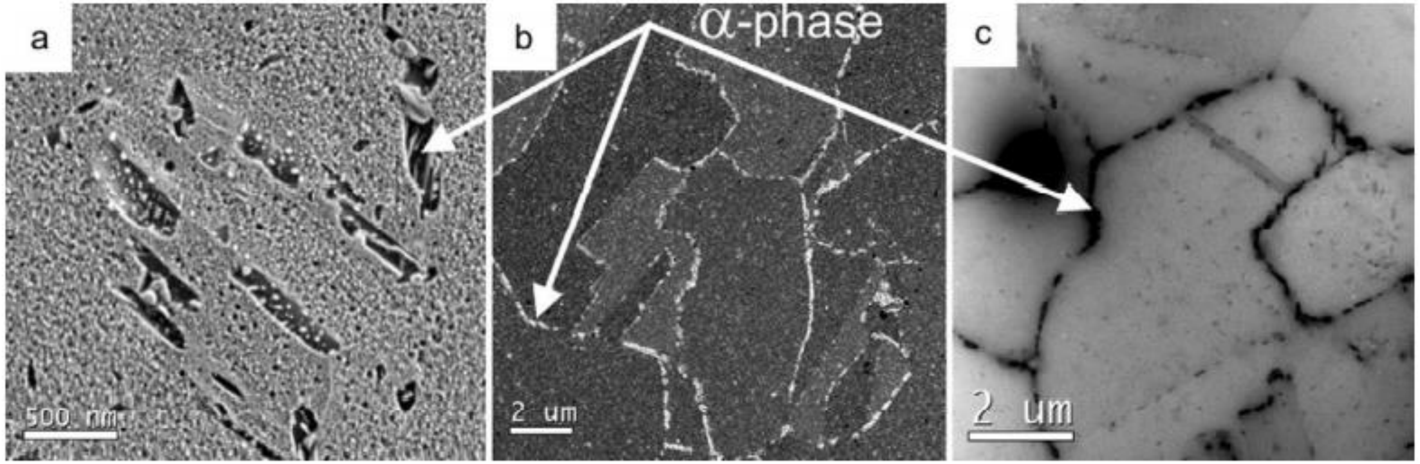
He concentration greater than 10 appm
NOT Weldable with current technology

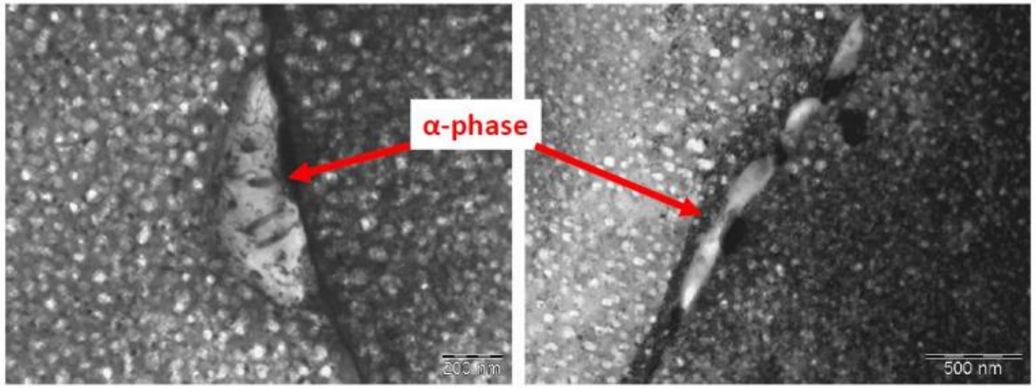


Weldability for CE reactor design at 75 ppm B and 60 EFPY

Development of Fe-rich ferrite phase in AISI 321 in BOR-60 reflector assembly after 41 years at very low dpa rates

Gurovich (Kurchatov) and Margolin (Prometey) groups





150 dpa peak
330-380°C

Reflector spectrum in Row 10 of BOR-60 has a very large epithermal neutron component that is strongly driving transmutation.

Increase in magnetism can be used to measure ferrite fraction but microscopy is often difficult because ferrite is dissolved during specimen production.

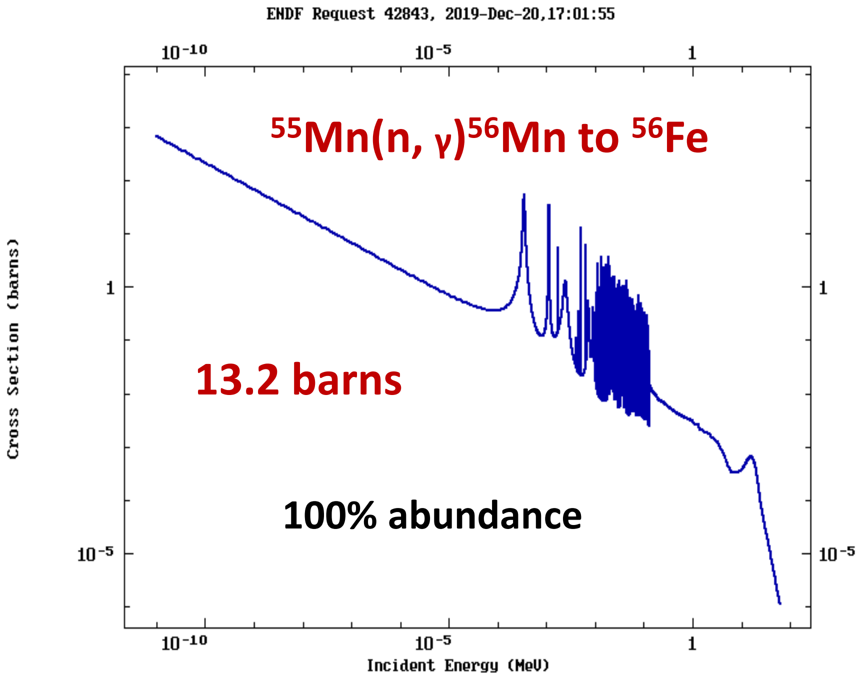
Conclusions concerning life extension to 80-100 years

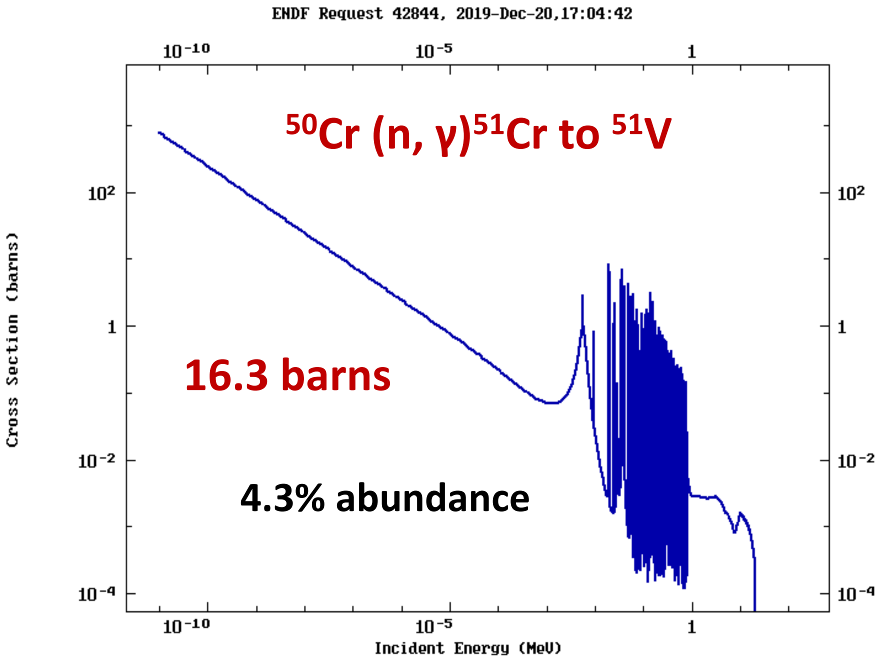
- **Changes in material properties and dimensions of stainless steels have been observed at doses up to ~150 dpa in fast reactors, which operate at much higher dpa rates and significantly higher temperatures than experienced in BWRs and especially PWRs**
- **Some of these changes will occur in LWRs but will be modified by differences in temperature, neutron spectrum and coolant.**
- **Well-known processes in PWRs such as cracking and corrosion will continue as the exposure increases but may be modified in nature or rate as transmutation increases and new phenomena emerge.**
- **Previously identified second-order phenomena have been found to be non-linear in their development and may become first-order in importance at higher dose.**
- **It is recommended that additional research and in-reactor surveillance continue to be conducted to identify new processes and their potential synergisms.**
- **It appears, however, that the life-limiting phenomenon of void swelling in fast reactors will not be a major problem for PWRs.**

Back-up slides

Transmutation for stainless steels has been previously thought not to be a significant issue, except for helium produced by ^{59}Ni (n, α) reaction.

At higher exposures, the burnout of Mn and burn-in of V may become an issue for phase stability and IASCC, especially when combined with reverse segregation at grain boundaries.





A major role of Mn in 300 series steels is to remove sulphur from the matrix and keep it off grain boundaries where it contributes to cracking.

Loss of Mn and increase in V will contribute to austenite instability, perhaps contributing to formation of ferrite.