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Thermal Annealing and Its Potential Mitigativet Changes in Material Properties in RPVs

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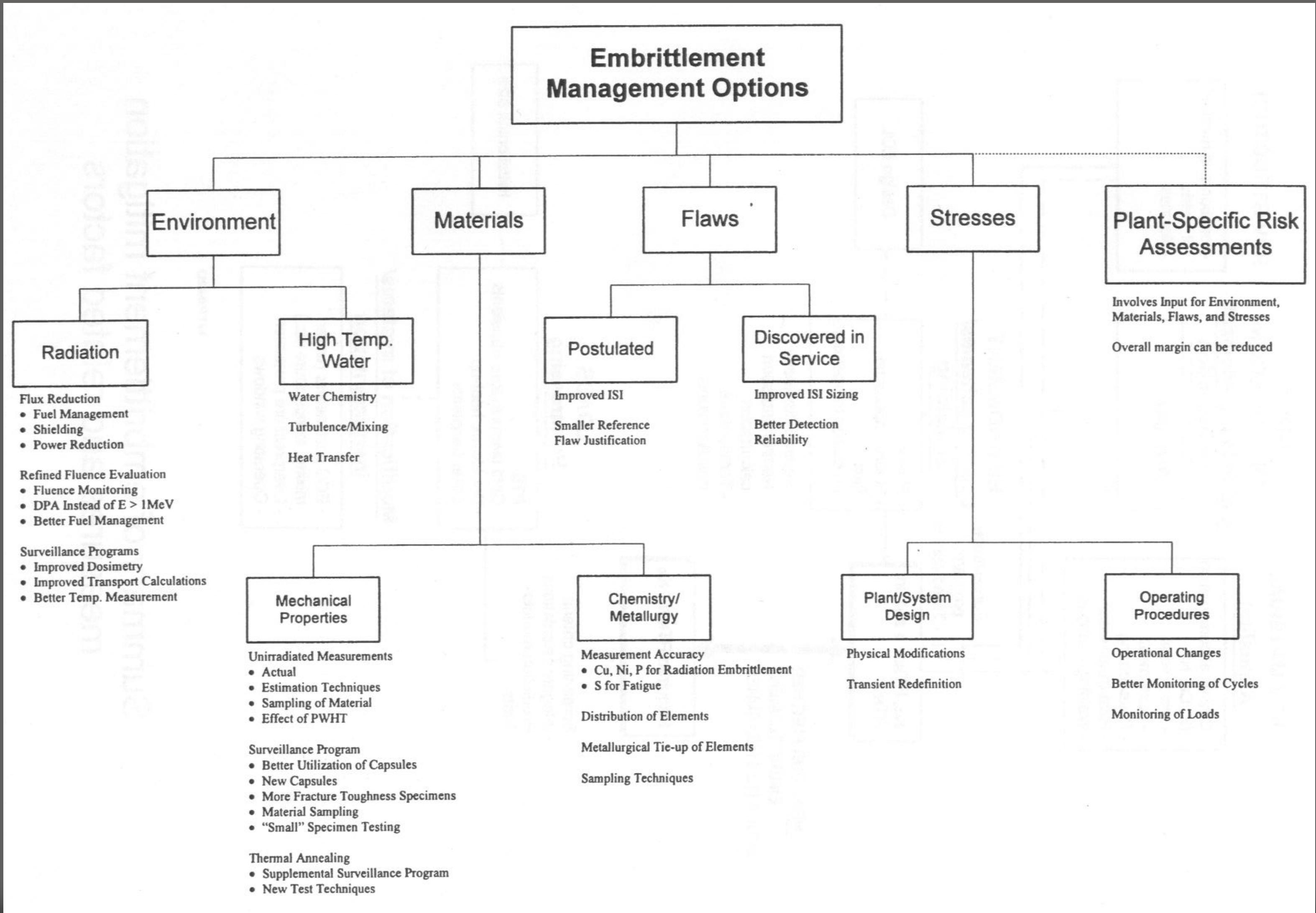
Overview of Embrittlement Management Options



Thermal Annealing

- Not a traditional “annealing” heat treatment -- much lower temperature (typically < 500°C) and about a one week time period (168 h)
- Wet vs. dry -- equivalent to low temperature (343^{o}C) vs. high temperature (430-500^{o}C) with different heating media (water vs. air)
- Different heating methods are possible for dry annealing: electric resistance heaters, indirect gas-fired heat exchanger, etc.

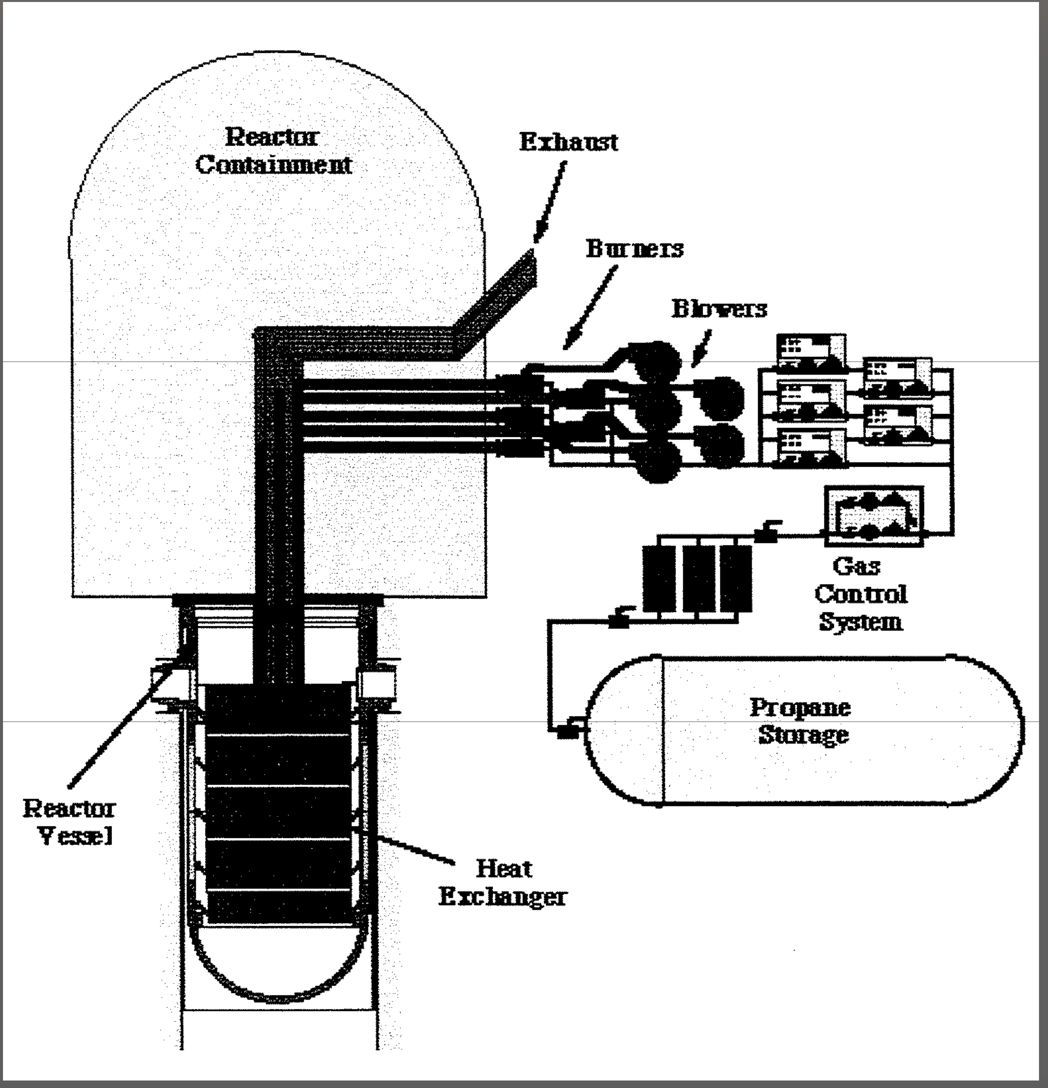
Successful Anneals in the U.S.

- First "wet" anneal on U.S. Army SM-1A vessel in Alaska in 1967
- Non-commercial vessel anneals in the late twentieth century
- "Dry" annealing of many Russian-design WWER-440 vessels has been very successful
- "Dry" anneal demonstration on cancelled Marble Hill vessel in 1996
  - Nozzle-supported four-loop Westinghouse design vessel
  - Successful demonstration in terms of temperature control and predictive aspects during the anneal

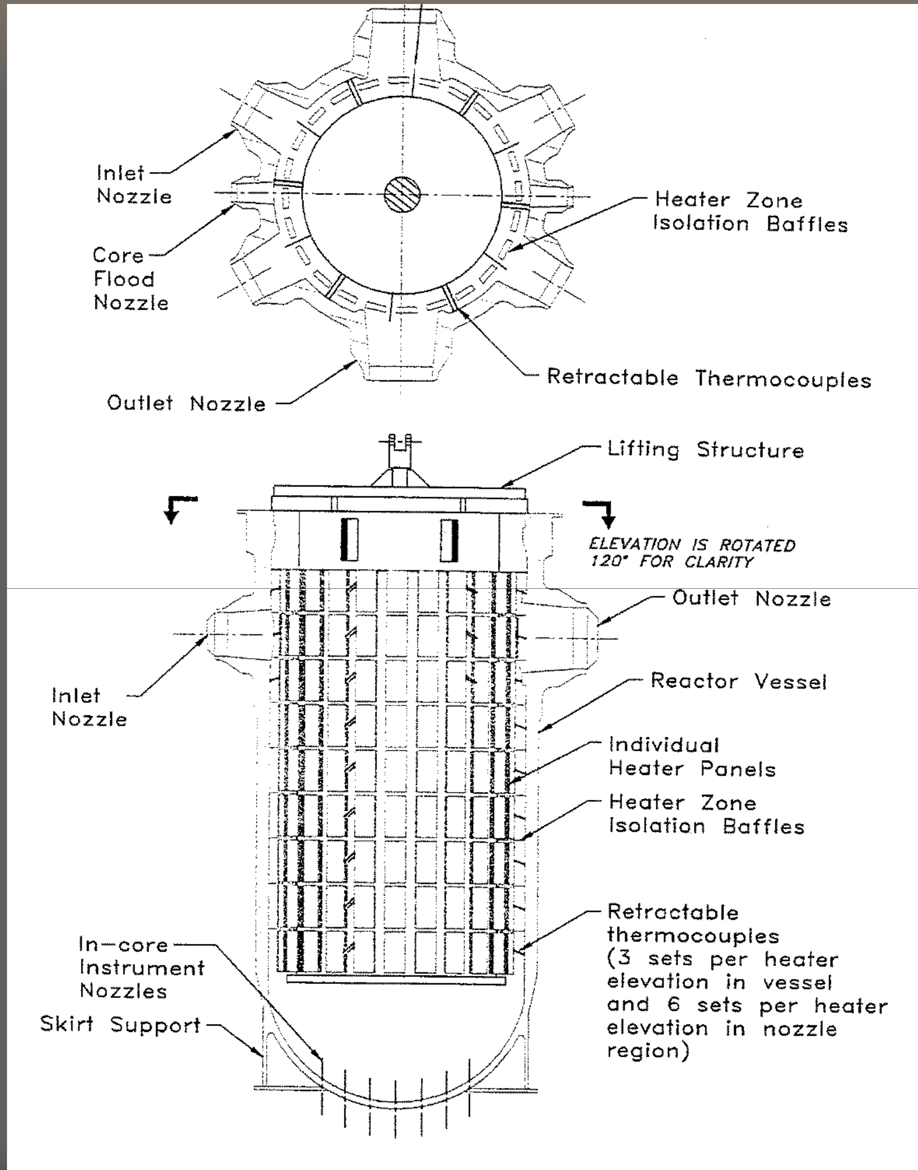
Additional History

- Yankee Rowe was planning to conduct a "wet" anneal
  - Operated at lower temperature (260ºC) than other PWRs
  - Plant was shutdown before annealing due to political issues
- Two "dry" annealing demonstrations initiated by industry and DOE in early 1990s
  - Marble Hill – indirect gas-fired can process (demonstration successful)
  - Midland – electric resistance heating designed by Russians (cancelled)
- Palisades was planning to "dry" anneal in 1998
  - Precipitated ASME Code Case N-557, NRC Annealing Rule 10CFR50.66, Regulatory Guide 1.162, and revised ASTM E 509
  - Annealing plans canceled once fluence re-evaluation allowed meeting end-of-life operating license

Indirect Gas-Fired Method



Electric Resistance Heating



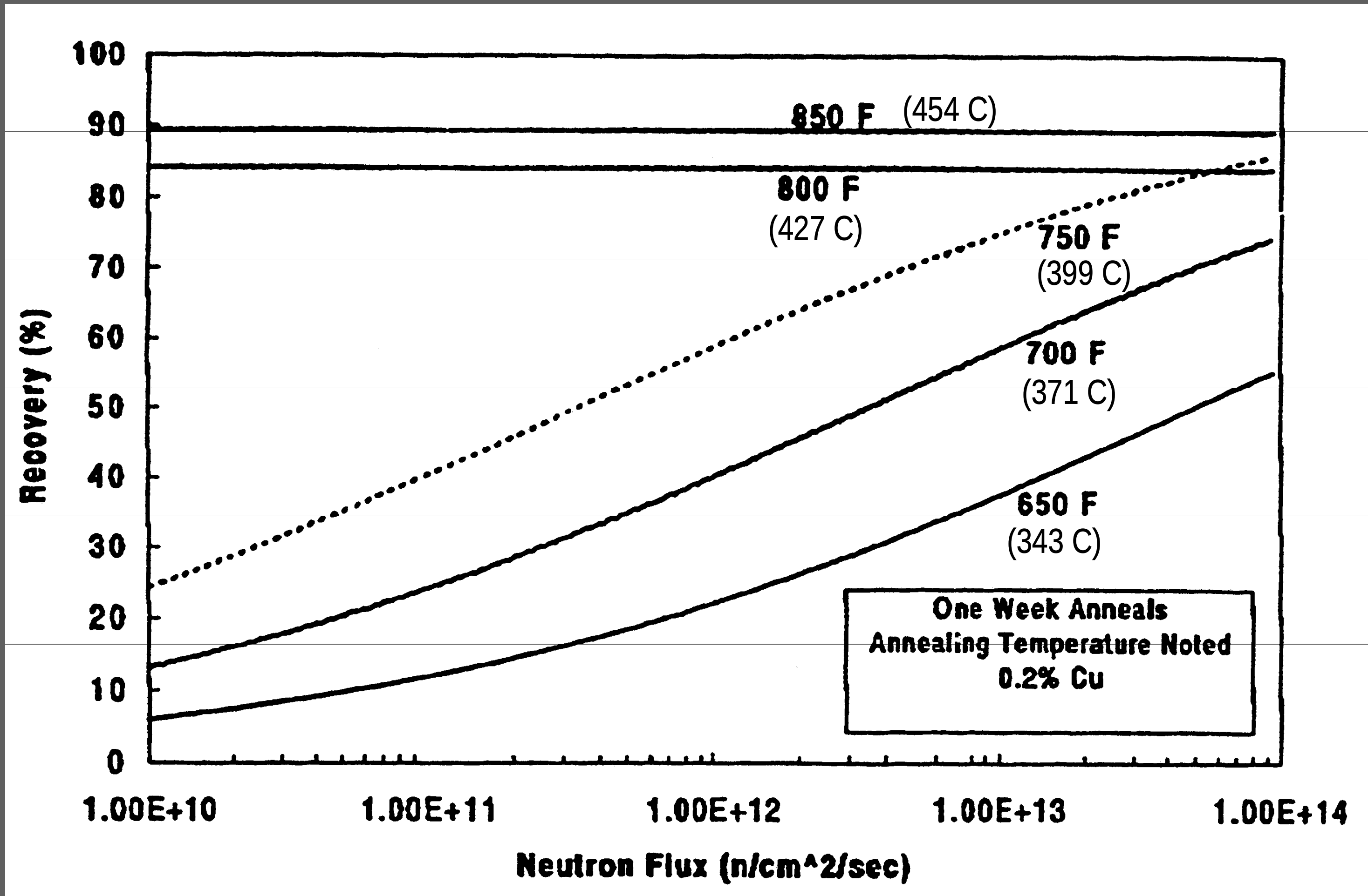
NRC Regulations/Guidance

- Annealing Rule in 10 CFR Part 50.66
- Regulatory Guide 1.162 on Annealing Program requirements and reporting
- Partial basis for Rule and Regulatory Guide 1.162 are found in NUREG/CR-6327
  - Predictive model for annealing recovery utilizing microhardness and CVN data to cover a broad range of conditions
  - Model incorporates annealing time and temperature and neutron irradiation fluence rate

Effect of Dose Rate on Annealing Recovery

- NUREG/CR-6327 model illustrates a strong annealing recovery effect due to the initial irradiation dose rate for annealing temperatures less than 427°C
- For most "dry annealing" considerations the effect of dose rate on annealing recovery is irrelevant since the temperature is well above 427°C
- Other data from an IAEA project on WWER-440 steels support no dose rate effects (MTR vs. actual surveillance) for annealing near 460°C

NUREG/CR-6327 Predicted Recovery



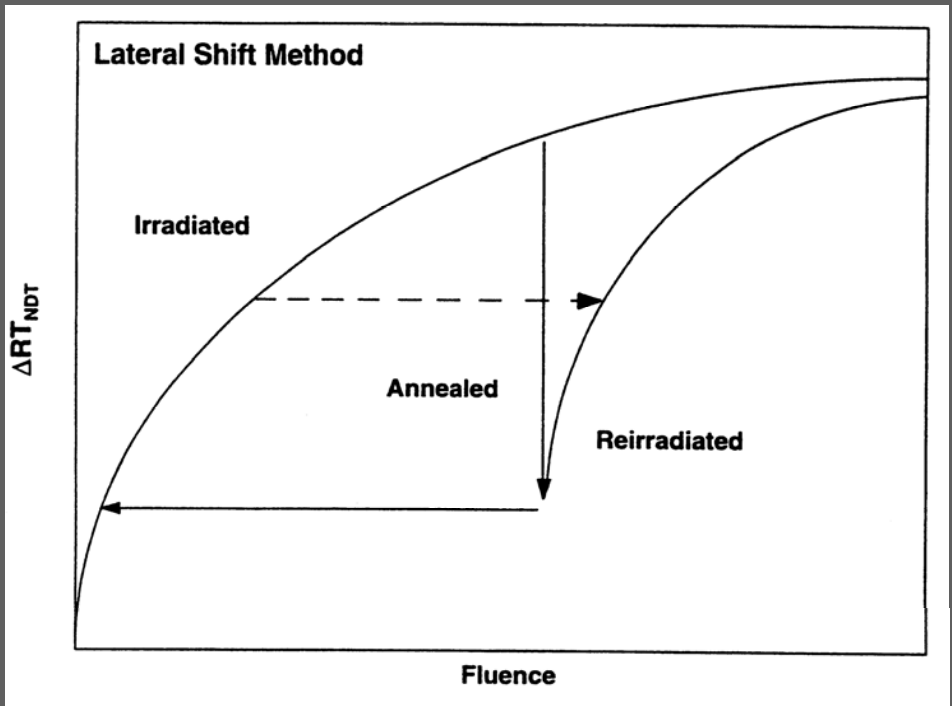
ASTM Activities

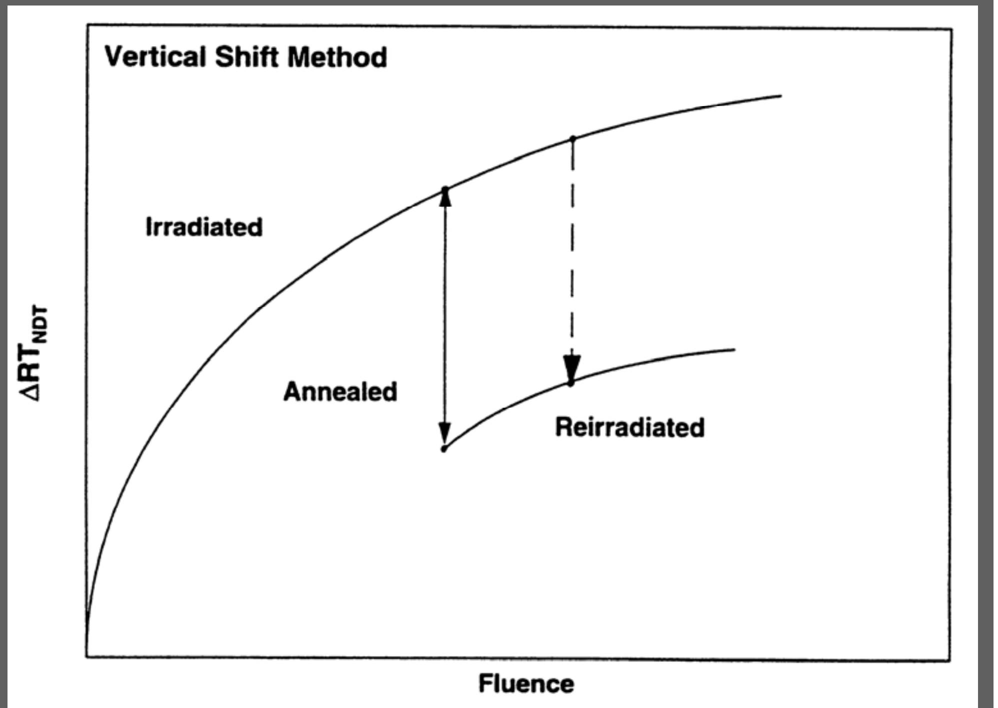
- ASTM E 509 was revised in 1997 to provide expanded general guidance on thermal annealing and associated material surveillance programs
- Recent revision has broken ASTM E 185 into two new Practices (E 185 on Surveillance Program Design and E 2215 on Testing of Surveillance Capsules
- Small specimen test techniques may be incorporated for annealing applications using other standards/guides (i.e., see ASTM E 636 on Supplemental Test Techniques and E 1253 on Charpy Specimen Reconstitution)

Re-Embrittlement is Key Issue in ASTM E 509

- ASTM E 509 provides detailed guidance in developing a supplemental surveillance program to measure reirradiation embrittlement
- Re-embrittlement database code using actual annealing and re-embrittlement data has been developed under EPRI sponsorship (IARDATA)
  - Annealing recovery generally follows NUREG/CR-6327 model
  - Re-embrittlement falls between the lateral shift and vertical shift models – to be decided by the user

Methods Used To Predict Re-Embrittlement





Potential for Intergranular Fracture – Caution in ASTM E 509

- Intergranular fracture can occur due to phosphorus segregation to grain boundaries in ferritic steels: coarse-grained HAZ, forging "ghost lines", and non-standard heat treatments (similar to temper embrittlement)
- There can be migration of phosphorus to grain boundaries during irradiation and subsequent thermal heat treating cycles
- For U.S. materials, the degree of phosphorus segregation does not appear to create any significant intergranular fracture potential, but some intergranular fracture areas are evident on fracture surfaces

ASME Code Case N-557

- "In-Place Dry Annealing of a PWR Nuclear Reactor Vessel (Section XI, Division 1)"
- Provides Code guidance for assuring design conformance after performing a thermal anneal heat treatment
  - Limits magnitude of thermally induced stresses in nozzle region
  - Effectively limits the maximum temperature of annealing to 505^{o}C
  - Passed in 1995
- Technical basis published by EPRI in TR-106967

Summary

- ASTM E 509-97 was developed partially in response to the planned anneal for the Palisades reactor vessel
- ASME Code Case N-557 was pushed through also to meet the needs of the planned Palisades anneal
- Regulation 10 CFR Part 50.66 and Regulatory Guide 1.162 were developed by the NRC in anticipation of the Palisades anneal
- A demonstration of the indirect gas-fired method heat exchanger was successfully conducted on the Marble Hill vessel
- Annealing of the Palisades vessel was cancelled due to revised dimensional measurements, fluence calculations, and regulatory uncertainty

Extended Operating License Issues

- Experience from development of U.S. Codes, Standards, and Regulatory requirements identifies some key issues:
  - Dose rate effect on annealing recovery for temperatures less that 427°C
  - Re-embrittlement rate and surveillance program requirements during extended life, considering any dose rate effects
  - Potential influence of intergranular fracture after annealing in high phosphorus content steels
  - Restricting the magnitude of thermally induced stresses in nozzle region effectively limits maximum temperature of annealing to 505°C

Other Possible Mitigative Options

- Fuel management
  - Can be cost efficient
  - Slightly reduces neutron flux
  - Power up-rating conflicts with benefits
- Shielding critical areas
  - Can be effective (SS and hafnium)
  - Expensive, so many plants have removed shielding
- Heat ECCS water
- Vessel replacement